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Charlotte Scheutz, Anders M. Fredenslund,
Gitte Bukh Pedersen, Alessio Pedicone and
Peter Kjeldsen

Department of Environmental Engineering
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Preface

The full title of the BIOCOVER project is *Reduction of Greenhouse Gas Emissions from Landfills by use of Engineered Biocovers*. The project is funded by the LIFE III ENVIRONMENT programme, the Danish Environmental Protection Agency, and RENOSAM and runs from August 2005 to November 2008. This report presents the outcome of Task 6 *Evaluation of methane oxidation efficiency of biocover system* as described in the project application (Biocover, 2005). Fakse Landfill serves as the demonstration landfill for the BIOCOVER project. Measurements of total emissions from Fakse Landfill were performed by FluxSense AB, Gothenburg, Sweden. The Department of Informatics and Mathematical Modeling at the Technical University of Denmark has contributed by lending out a high accuracy Trimble RTK GPS.

Summary

The objective of task 6 “Evaluation of methane oxidation efficiency of biocover system” was to evaluate the efficiency of a biocover system constructed at Fakse Landfill to reduce the emission of methane from the landfill to the atmosphere. Based on previous tasks of the overall BIOCOVER project where the gas generation at the old part of the landfill (where the biocover system is installed) was estimated and the capacities of the cover improvement materials to oxidize methane a cover improvement plan was evaluated, the needed area of bio-active materials was estimated. Additionally, the plan included proposed activities for reducing the unwanted methane releases through the leachate collection system and hot spot areas localized at the slopes of the landfill. The biocover system consisted of 10 biocover windows installed on Fakse landfill section I with a total area of 5000 m2. The biocover material used was untreated 3 to 4 years old composted garden waste. The thickness of the compost layer was one meter, with a 10 cm gravel “gas distribution” layer beneath. The options of placement of the biocover windows were somewhat limited due to use of large parts of section I for temporary storage and treatment of combustible waste, storage of compost, and disposal of sludge.

The cover improvement plan included plans for avoiding uncontrolled releases of methane: initially all gas leaking leachate wells were sealed using plastic caps and the hot spot areas on slopes were sealed by covering the areas with additional clay soil layers. However, initial surface methane screening initiated to ensure that no more uncontrolled methane releases exist, elucidated that more improvements has to be carried out to enhance the gas distribution into the biowindows. The screening showed that the soil around the leachate wells was leaking methane, and an abandoned leachate recirculation system present on stage 1 was a significant route of methane release. Another problem was that the sealing of all the leaking leachate wells had redistribution the gas to the leachate pumping station. Also the presence of large quantities of clay soil underneath selected biowindows affected the gas load to the biowindows.

The following improvements were made: sealing soil surface around leachate wells using bentonite, covering leachate recirculation wells with clay, installation of water locks on the inlet pipes of the leachate pumping station, and replacing low permeable material beneath windows on disposal unit 1 with tree roots to increase methane load.

After the additional improvements were made, more methane screening was carried out to identify hot spots of methane release. The screening showed that soils in the vicinity of the leachate wells were more permeable than the soils covering the rest of the landfill, resulting in methane emissions. Also some of the landfill slopes were leaking despite the effort for sealing these areas. Hot spots were also identified on most of the biowindows especially close to the borders of the biowindows. Additional activities were initiated on selected biowindows to elucidate the reasons to the hot spots on the biowindows.

The additional detailed studies were carried out on two of the biowindows, V1.1 and V7. Surface fluxes of methane and carbon dioxide was measured by mobile flux chambers. Also gas profiles of the four main components (methane, carbon dioxide, oxygen and nitrogen) were obtained. Besides, compost samples were taken from one of the windows (V1.1) to evaluate the compost respiration and the methane oxidation

capacities of the in-build compost. The compost samples were taken out from hot spot areas of the biowindow.

The detailed studies revealed that problems with contact to the underlying gas-generating waste still exists despite the efforts for improving the contact by excavation of trenches and placement of high-permeable materials beneath the biowindows. The studies showed that most of the loading to the biowindows is through the gas distribution layer located below the soil cover. This pattern creates the hot spot areas at the borders of the biowindows – the gas distribution layer underneath the compost layer cannot distribute the gas loading further to a larger fraction of the windows area. The studies, however, also showed that there may be significant methane oxidation processes in the gas distribution layer since the methane concentrations in the gas originating from the distribution layer were much lower than observed in deep raw gas samples.

The detailed studies of compost respiration showed that in areas of biowindows with low gas loading the observed surface fluxes of carbon dioxide mainly originate from compost respiration. They also showed that the respiration rate was generally higher in compost which has been affected by high methane loading through months. The fact that observed fluxes of carbon dioxide may originate from three sources (originally present in the landfill gas, produced by methane oxidation, and produced by compost respiration) challenges the ability of using carbon mass balances of the bio-active compost layer, however the carbon mass balances revealed that significant methane oxidation is taking place in the hot spot areas. These findings were supported by the observed gas profiles and the initial analysis of stable carbon isotopes. However, it is obvious that the very uneven gas load of the biowindow as a result of the mainly horizontal gas flow to the biowindows creates hot spots with high gas loads resulting in high methane oxidation rates. This was supported by batch incubation of the hot spot compost in the laboratory. The high loads, however, creates low retention times in these regions resulting in an incomplete oxidation of methane and surface methane emissions.

In order to obtained an evaluation of the overall ability of the established biocover system to reduce the methane emission from the landfill, the whole landfill site emission measurements as introduced as part of the baseline study (Task 3) was repeated in four times in the period after the biocover system was established. The average baseline methane emission before installation of the biocover system was about 31 kg/hour as already report in the Task 3.1-report. During the first two campaigns conducted after biocover system establishment a little higher methane emission of 36 kg/h was observed. The last two campaigns conducted in more than a year after the biocover installation showed both significantly smaller emissions in comparison to the baseline study. The emission from the old section was measured to 22 kg/hour indicating an overall reduction of 9 kg/hour corresponding to about 30% in comparison to the baseline study. These results indicate that the biocover system after all has an ability to reduce the methane emission to a certain extent, despite of all the presented obstacles for obtaining an efficient biocover system.

Besides the whole landfill site measurements, samples were taken of ambient air up and down wind of the landfill, together with samples of deep landfill gas. The samples are being analyzed for stable carbon isotope content the contained methane in order to estimate the average oxidation efficiency of the biocover system. The results is to be

compared with the before/after approach using the whole site emission measurement. The result of the stable isotope analysis was not ready yet at the reporting deadline of the BIOCOVER project, but will be part of the scientific articles which are in progress and will be published as part of the after-LIFE communication plan.

Table of contents

Introduction

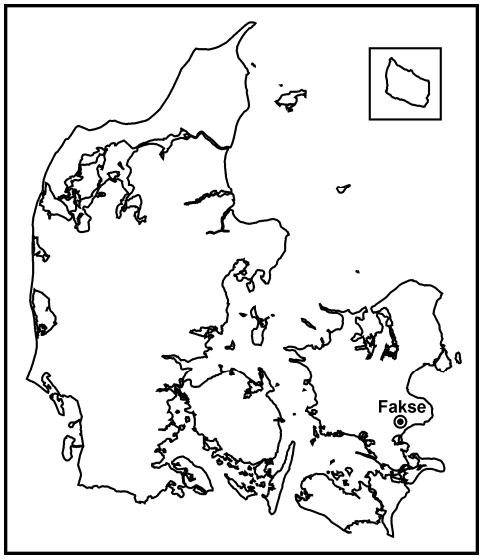
Most landfills contain organic wastes which produce biogas, containing methane and carbon dioxide. Emission of methane from landfills is a serious environmental problem and is explicitly mentioned as a source for greenhouse gasses in the EU *Sixth Environmental Action Plan*. In a global perspective, landfills accounts for 7-20% of the anthropogenic methane emissions to the atmosphere.

Landfill gas (LFG) is at some landfills extracted and utilized for energy purposes leading to methane emission reduction. However, it is not always feasible to extract and utilize the landfill gas. In these cases the gas is flared with risk of producing toxic combustion products, or is just escaping to the atmosphere.

A low-cost alternative could be to improve the top covering of the landfill in order to optimize the biological methane oxidation in the cover. Laboratory experiments have documented that a very high methane oxidation rate can be obtained in bio-covers, thereby reducing the methane emission significantly. The biological methane oxidation transforms methane into carbon dioxide, and since methane has a 21 times stronger global warming potential than carbon dioxide, a significant reduction in the source to global warming is obtained. Biocovers may also be a very cost-effective supplementary method at landfills with landfill gas utilization, since the efficiency of the gas extraction system often is in the range of 50-60 %.

The BIOCOVER project has the objective to perform a full scale implementation of engineered bio-covers and to document the methane reduction efficiency. Fakse Landfill in Southern Zealand, Denmark, serves as a demonstration landfill for the implementation of the technology.

Fakse Landfill is divided into two sections. The oldest section which was in use from 1981 until 1997 has been the focus of the project activities. This part of the landfill has an area of 12 hectares and has received mixed waste. Approximately 600,000 tonnes of waste has in total been disposed of at the older part of the landfill. The landfill is typical for Danish landfills of similar age.



Map of Denmark showing the location of the study landfill, Fakse Landfill

This report concerns results of performance testing of the biocover system installed at Fakse landfill in 2007 (Task 6 Evaluation of methane oxidation efficiency). Emissions are compared to values obtained during baseline studies, prior to installation of biocover. These results are documented in the project reports D 3.2.1 A: "Measurement of spatial variation in emissions" and D 3.2.1 B: "Whole site methane emission". Design basis of the biocover system is described in the project report D5.1.1: "Cover improvement plan". Some modifications to the cover improvement plan were made during construction of the system as result of initial performance testing. These changes are described in this project report.

1 Installation of the biocover system

The main objective of the biocover system at Fakse landfill was to reduce methane emission from the site, which reduces impact on global warming. Secondly, the system had to be designed in most part using materials and resources readily available at the site, since a cost effective system (€/tons CO_2 GWP removed) was another important objective of the biocover project.

Design plans of the biocover system are described in the project report "Cover Improvement Plan" (Fredenslund et. al, 2007). A summary of the design plan, as well as adjustments made during construction are described in this section. Initial performance measurements revealed the necessity of further improvements. These are described in section 3.

1.1 Design of biocover system

The biocover system was designed to reduce methane emissions by optimizing conditions for biological oxidation of methane in high permeable compost filled regions of the cover of the landfill. Composted garden waste is known to be a suitable material for these systems, which in turn are available at low cost at many landfills, including Fakse landfill, since they often receive large amounts of garden waste for treatment. At section I on Fakse landfill, deposited waste was covered with low permeable clayey soil. The idea of the project was to replace part of the existing low permeable soil cover with high permeable regions (Biocover, 2005). In this report, these high permeable regions are referred to as "biowindows", "biocover windows" or simply windows. The windows consist of a gravel layer to distribute gas to an overlying compost layer, where methane oxidation occurs. Planned thicknesses of the layers were 100 cm (compost), and 15 cm (gravel layer).

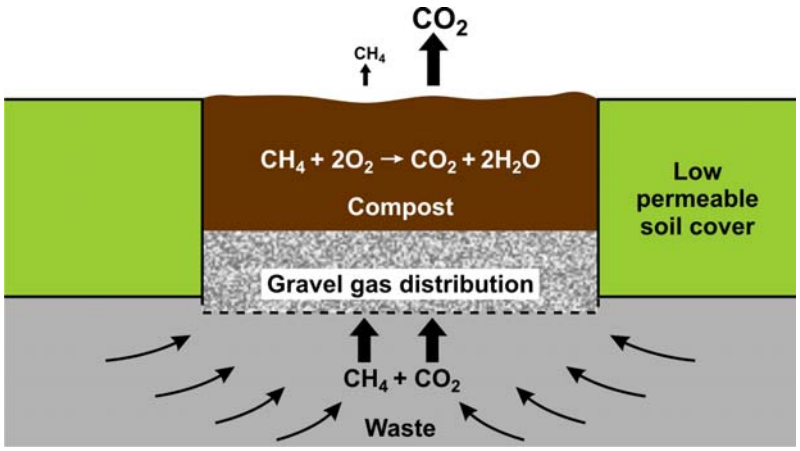


Figure 1.1. Biocover window

To determine the necessary total area of the biocover windows at the site, two main design parameters were seen as important to establish: Methane load, which is amount

of methane that flows through the biocover system per day, and methane oxidation capacity of the biocover material

Results from modeling of the methane production at Fakse Landfill (Lemming & Kjeldsen, 2006) and results of methane emission measurements (Fredenslund et. al, 2006) & (Scheutz et. al, 2007) were used to quantify methane load – both in terms of total methane load and spatial distribution at the site. The total methane load was assumed to be equal to the total emission: 740 kg CH_4 d^{-1}, which was determined through measurement of total methane emission from section I using tracer release and downwind measurement by FTIR. These measurements are described in a previous project report (Scheutz et. al, 2007). Gas production modeling done for each of the 7 disposal units on the site was used to determine the distribution of methane load, and thereby the distribution of "biocover area" to the different parts of the landfill.

Preliminary results from Task 4 "Testing improvement strategies" were used to establish methane oxidation capacity. The anticipated methane oxidation capacity was 150 g CH_4 m^{-2} d^{-1} (Biocover, 2005), and this value was close to the oxidation capacity measured of the biocover materials (119 to 154 g/m^2/day for over the first 70 days) during testing using column setup. The compost material chosen for the biocover windows was untreated composted garden waste (3-4 years old), since this material was available in large amount at Fakse landfill, and this material was found to be stable with regards to methane oxidation (Pedersen et. al, 2008).

From the measured total load, and the measured methane oxidation capacity of the chosen biocover material a minimum total area of the biowindows was found to be 5000 m^2, assuming equal distribution of methane load and that all methane passed through biowindows. This area was far higher than mentioned in the project proposal (8*160 m^2), which was due to a higher than anticipated measured total methane emission. The total area of the biocover windows was therefore set to 5000 m^2.

Table 1.1. Area, percentage of methane production calculated using methane production modeling and planned biocover area of each of the seven disposal units (Fredenslund et. al, 2007).

Disposal unit	**Area of disposal unit (m^2)**	**Percentage of total methane production**	**Biocover area (m^2)**
Unit 1	22 000	8 %	400
Unit 2	11 000	7 %	400
Unit 3	11 000	6 %	300
Unit 4	14 000	16 %	800
Unit 5	17 000	17 %	800
Unit 6	22 000	13 %	700
Unit 7	24 000	32 %	1600
Sum	121 000		5000

The disposal units containing older waste (Unit 1, 2, 3) were calculated to produce far less methane per surface area unit than the units containing newer waste. Therefore the largest windows were planned for the newest disposal units.

Since more than half of the methane emitting from the site was found to occur through the leachate collection system (Fredenslund et. al, 2006), simple gas barriers were made to prevent gas from emitting through leachate collection wells. The gas barriers

were removable PVC caps covering the top of each leachate well. The edges of the caps were sealed using neoprene rubber seals between the concrete sides of the wells and the caps, and tightening the caps was done using stainless steel bands.

The baseline study of methane emissions from Fakse landfill showed significant emissions from the sides of a few of the slopes of the soil cover (Fredenslund et. al, 2006). To reduce these emissions, two slopes were set to be added 10 – 20 cm clay. A smaller third slope on disposal unit 7 where very high emissions were measured during the baseline study did not exist at time of designing the biocover system due to further disposal of waste.

1.2 Construction of biocover system

Construction of the biocover system at Fakse landfill was started May, 2007 and completed August, 2007. The locations of the windows on the temporarily covered part of the landfill (disposal units 4, 5, 6 and 7) were modified somewhat compared to the original plan. On unit 5, it was not possible to place a biocover window. Instead, a larger window was constructed on neighboring unit 6. On unit 7 one large biowindow was constructed instead of several smaller ones to reduce cost. The planned location of window 4.2 was not usable, due to deposit of soil intended for later final covering at that location. Another location nearby was found instead.

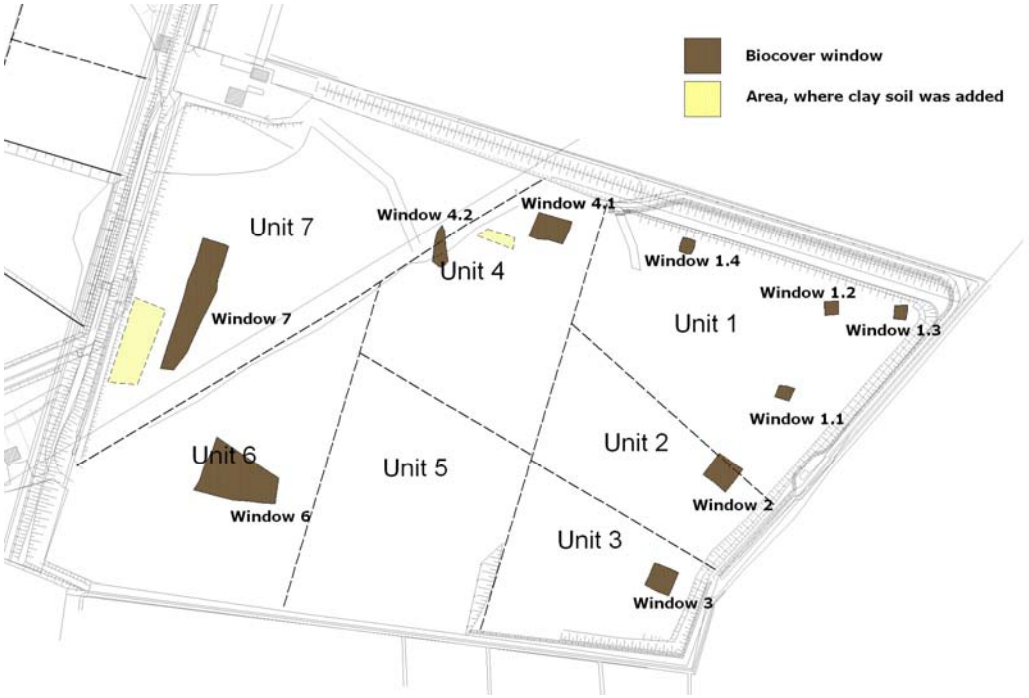


Figure 1.2. Locations of biocover windows (brown areas) and locations of slopes, where clay soil was added to reduce gas permeability of the cover (yellow areas).

It was not practical to place biocover windows in the centre of the landfill (see figure 1.2), since this area was used for temporary storage of waste, compost and materials as well as sites for sludge disposal. Placing the windows at the location shown also placed many of them near slopes in the soil cover, where landfill gas emission was

seen. Figure 1.2 shows actual locations of the biocover windows. The borders of the windows were measured using a precision GPS. The approximate locations, where soil was added to reduce permeability of cover soil are also marked.

During construction, concerns about the permeability of the deposited waste beneath windows 2, 6 and 7 caused some further measures to be taken to increase gas transport to the windows. Beneath window 2 an approximately 4 meter thick layer of deposited clayey soil was found. To increase the likelihood of LFG reaching the window itself, a grid of 10 cm diameter holes were drilled through the soil layer, and filled with gravel. Screening of methane concentrations in these holes prior to filling the window with gravel and compost did show that LFG was passing through the holes. A grid of 16 holes was dug on window 2 with an approximate spacing of 5 meters.

At windows 6 and 7, the waste beneath the excavated cover soil was found to be mixed with clay – possibly caused by adding and removing temporary soil covers in the active period of the disposal units. Since both these windows were established close to slopes of the soil cover, where high LFG emissions were seen during the baseline study, a high risk of LFG emitting through the slopes rather than passing through the windows was of concern. To reduce this risk, trenches at the edge of the windows closest to the slopes were dug in the waste and filled with large tree roots, thereby creating "corridors" for gas to pass through to the biocover windows rather than to the slopes. The trenches were approximately 6 meters long, 2 meters wide and 4 meters deep. Three trenches were dug in both windows 6 and 7.

As planned, caps were installed on leachate collection wells, to avoid LFG to emit from these wells rather than passing through the biocover windows. All wells, where significant emissions were measured during the baseline study were fitted with caps – 13 in all[1].

Figure 1.3. Cap on leachate well installed to prevent LFG emission. These flexible caps were seen to bulge out shortly after fitting them on the leachate wells.

[1] Wells D2, D3a, D4, D4a, D6, D8, D9, D10, D11, D12, D13, D14 and D15

Instead of installing a gas distribution layer with a thickness of 15 cm as planned, 10 cm layers were used. This allowed the use of existing root blocking gravel (average grain size ≈ 5 mm) as gas distribution layers, where windows were constructed on a finally covered part of the landfill. In this way cost was also reduced, since gravel had to be purchased. Figure 1.4 shows a biocover window after excavation and installation of gas distribution layer (top), and a finished window (bottom).

Figure 1.4. Biowindows during construction (top) and after construction (bottom).

2 Initial measurements of biocover performance

A monitoring plan was setup prior to finalizing the biocover system at Fakse landfill. The main focus of monitoring was to measure performance of the biowindows in terms of methane oxidation. Another focus was to perform leak testing, which involved screening of methane concentrations at the landfill to investigate the amount of landfill gas emitting through other pathways than the biocover windows. If large leaks were to be found, measures were to be taken to reduce the emission through these leaks.

In this chapter, results of initial leak search and "local" measurement of biocover performance is described.

2.1 Leak search

Upon installing biocover at Fakse landfill, leak searches were made to evaluate the extent of bypass by landfill gas of the biowindows. Methane emitting from the leachate collection system, and emission through soil cover on slopes was in focus. These locations were observed to be significant emission sources during the baseline study on emissions (Fredenslund et. al, 2006).

Observations made regarding methane emissions are listed below. The measurements were performed with a FID detector, capable of measuring 0.5 to 2000 ppmv methane. The instrument is described in appendix 1. The FID screening was done on October 25th 2007 under stable barometric pressure (see figure 2.3)

Disposal unit 1

Methane concentration slightly above background levels were measured at biowindows 1.1 and 1.2. Near two leachate wells, which were not capped during installation of the biocover, concentrations higher than 2000 ppm were measured indicating significant emissions from these wells. These wells were a part of a leachate recirculation system taken out of use.

Disposal unit 2

Methane concentrations higher than 2000 ppm were measured near and inside of the main leachate pumping station. This was far higher than measured before installation of the biocover, and was probably due to capping of the leachate wells leading gas to flow through the pumping station.

No other leaks were identified on disposal unit 2

Disposal unit 3

No leaks found

Disposal unit 4

Concentrations up to 50 ppm were observed on a corner of window 4.1. Elsewhere: background levels. Concentrations above 50 ppm were measured on a slope near leachate well D8

Disposal unit 5

No leaks found

Disposal unit 6

No leaks found

Disposal unit 7

Four methane emission hot spots were found on window 7. Three of these were located where trenches were dug to increase methane load as described in chapter 1. Concentrations up to 160 ppm were measured.

Generally concentrations were higher than 10 ppm on the slope on unit 7 where clay was added to reduce emissions. 1/3 up the slope, many hot spots were found, where methane concentrations measured between 150 and 500 ppm.

2.2 Tracer release measurements

The leak test suggested that significant leaks were at the main leachate pumping station on disposal unit 2 and leachate recirculation wells on disposal unit 1. It was therefore chosen to measure the flow rates to decide whether or not to make modifications to reduce gas flow from these installations. To do this, a tracer release method was used. The same method was used to quantify emissions from leachate wells during the baseline study of emissions described in Fredenslund et. al, 2006.

To measure methane emission, carbon monoxide tracer gas at a constant flow rate was added to the well or pumping station. Using an Innova gas monitor, concentrations of tracer and methane were measured downwind.

Table 2.1. Methane emissions measured at leachate pumping station and leachate recirculation wells

Location	**CH_4 emission (kg d^{-1})**
Pumping station	44.5
Recirculation well R1	20.4
Recirculation well R2	9.4

The total methane emission from the site measured during the baseline study prior to installing the biocover windows was 740 kg CH_4 d^{-1} (Scheutz et. al, 2007b). In light of this, it was concluded that the emission from the leachate pumping station and recirculation well was significant (see table 2.1), and improving the biocover system to reduce these emissions was prioritized.

2.3 Performance measurement campaigns

In order to evaluate the methane oxidation performance of the biocover windows over the season monthly campaigns were initiated with 12 fixed measuring nests. The measuring nest included a surface flux chamber, a deep flux chambers and a multilevel gas probe. These are described in Appendix 1: Equipment. Three windows were chosen with 4 randomly placed nests in each of them. The windows were window 1.1, window 1.4 and window 7, and the placement of the monitoring nests

can be seen in figure 2.1. The performance of the deep flux chambers was evaluated and the results can be seen in Appendix 2. The mass balance when compared to the surface flux chambers showed that the deep flux chamber measurements were not useful as the carbon loss over the 4 campaigns were 94%±10% corresponding to 16±21mole C m^{-2} d^{-1}. Therefore, the method did unfortunately not yield results which could be used with high enough confidence to determine landfill gas loads. Further method development and testing is necessary.

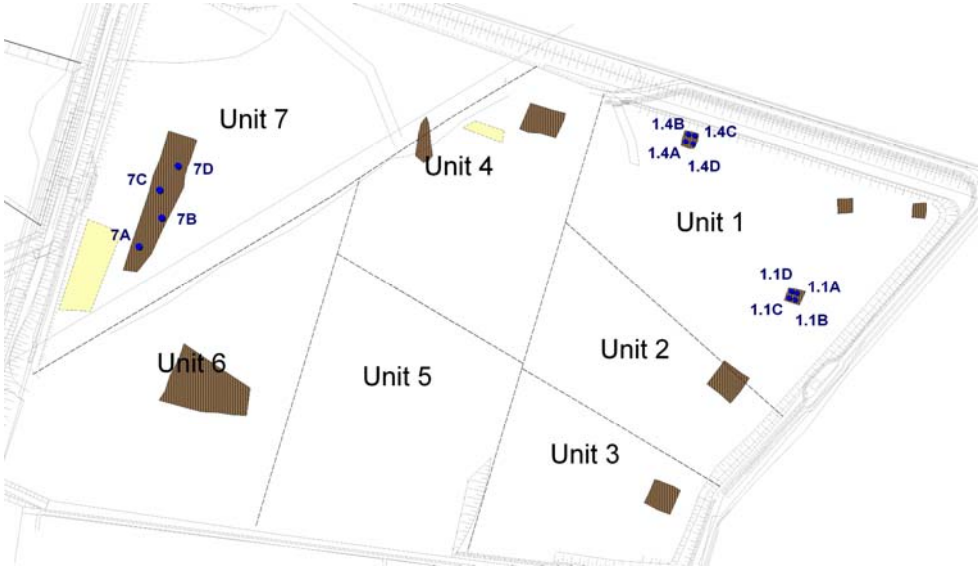


Figure 2.1. Placement of the 12 nests of flux chambers, deep flux chamber and gas probes. 4 in each window in window 7, window 1.4 and window 1.1.

Window 1.1 was the pilot scale window, finished and equipped prior to the other windows; May 2007 and therefore measured solely in October 2007, subsequently all 12 nests were measured; November 07, December 07 and January 07. Hereafter it was decided to halt the monthly measurements and try to improve the system to get a better load to the windows.

Results

In figure 2.2 the weather conditions under the 4 initial measuring campaigns can be seen.

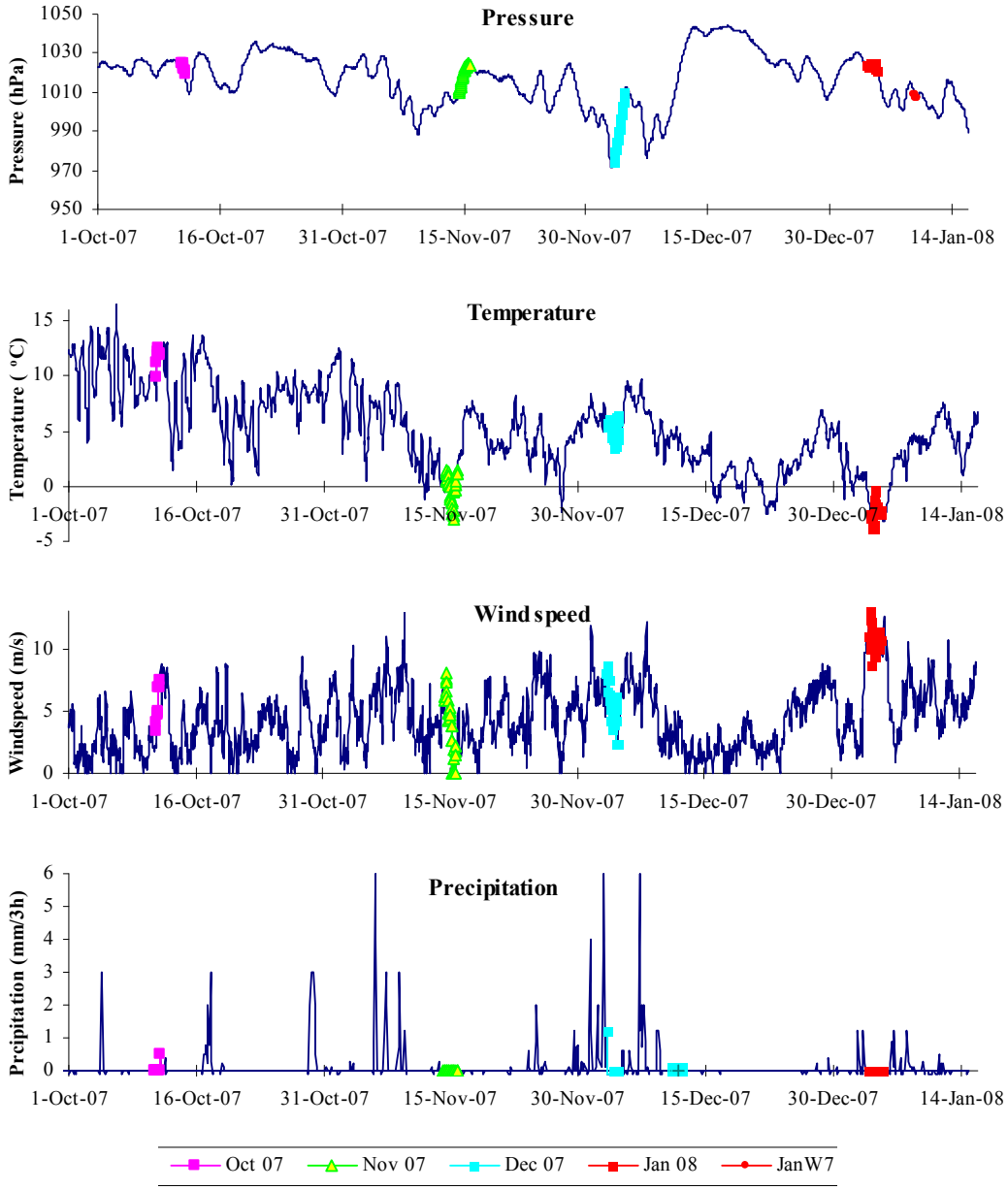


Figure 2.2 Pressure, temperature and wind speed before, under and after the 4 initial measurement campaigns. Data from Danish Meteorological Institute, Brandelev Station 14.5 km SW of Fakse Landfill.

In Figure 2.2 and Table 2.2 it can be seen that both the November and December campaigns were done during increasing pressure ($\Delta P>0.6 hPa\ h^{-1}$), though the pressure change 24hours before the Dec 3rd (1.1) campaign was -0.9hPa h^{-1} . The January campaign was done under more stable pressure conditions (0 to -0.44hPa/h) (-0.26-

0.04hPa h^{-1} 24hours prior to the measuring campaign), but with very high wind speed (>10m/s for 1.1 and 1.4) and very cold weather (T<0°). Also the November campaign was done with temperatures under zero degrees Celsius causing the top 5 cm of the biocover window to be frozen. The December campaign was done after a heavy rain event, which has previously been reported to affect emissions from a compost biocover window (Cabral et al. 2008).

Table 2.2: Measurement campaigns and results prior to the improvement of the biocover system. Red numbers present indicate carbon dioxide emission above expected load. Green numbers represent zero carbon dioxide emission. Blue numbers indicate methane concentrations above 1vol% in the bottom of the profile.

	Date	ΔP^a	ΔP^b	T^c	*Wind Speed*[c]	*Emissions*		CH_4 *Conc*[d]	CO_2
		hPa h^{-1}	hPa h^{-1}	C°	m s^{-1}	g CH_4 m^{-2} d^{-1}	g CO_2 m^{-2} d^{-1}	vol%	
1.1A	Oct 11th -07	-0.04	-0.24	11.7	5.3	-0.20	101	0	15.8
1.1B						-0.09	154	**1.2**	20.7
1.1C						-0.09	**345**	**4.2**	20.1
1.1D						-0.02	66	0	11.6
1.1A	Nov 15th-07	0.59	-0.10	0.4	1.2	-0.1	14.1	0	6.3
1.1B						0.1	17.5	0	12.7
1.1C						**0.4**	33.3	**2.0**	18.0
1.1D						0.0	122.2	0.6	14.6
1.4A	Nov 14th-07	0.16	0.68	1.1	6.6	-0.1	6.3	**9.1**	4
1.4B						0.0	15.7	0.4	4.7
1.4C						0.0	26.8	0.3	16.8
1.4D						0.0	32.2	0	4.3
7A	Nov 14th-07	0.16	0.68	0.9	6.6	0.0	**0.0**	0.9	4.3
7B						**2.2**	94.3	**4.2**	10.3
7C						0.0	1.3	0.6	13.8
7D						-0.1	**-1.8**	0	1.3
1.1A	Dec 3rd-07	-0.9	1.0	5.7	7.3	0.0	10.9	0.2	3.2
1.1B						0.0	33.5	0	0.3
1.1C						0.0	12.5	**1.2**	15.9
1.1D						0.0	47.4	0	6.1
1.4A	Dec 4th-07	1.1	1.1	5.2	4.3	0.0	4.6	0	5
1.4B						**1.6**	45.0	**5.2**	14.9
1.4C						0.1	12.4	**20.4**	24.4
1.4D						0.0	8.0	0.5	8.7
7A	Dec 11th-07	0.8	0.9	4.8	3.1	-0.1	**0.0**	0.17	1.1
7B						0.0	198.7	0.46	5.5
7C						-0.1	35.0	0.36	12.8
7D						-0.1	**-1.9**	1.60	6.3
1.1A	Jan 4th-08	0.01	-0.44	-2.4	10.7	0.0	**0.0**	0	1.2
1.1B						0.0	1.1	0.1	4.9
1.1C						0.0	167.7	0	17.9
1.1D						0.0	**0.0**	0	3.3
1.4A	Jan 3rd-08	-0.26	-0.01	-3.3	10.7	0.0	**-1.0**	**7.7**	3.2
1.4B						0.0	**0.0**	0	8.2
1.4C						0.0	**0.0**	0.1	14.9
1.4D						0.0	**0.0**	0	4.8
7A	Jan 9th-08	0.04	-0.16	4.0	5.9	**137.4**	190.1	**1.4**	8.5
7B						0.5	23.1	0.1	2.8
7C						0.0	0.6	0.00	16
7D						-0.1	**-0.7**	0.00	2.2

[a] The pressure gradient 24h prior to the measuring campaign [b] The pressure gradient is the pressure difference over the measuring day from 8am to 4pm. [c] Average between 8am-4pm. [d]Concentration in the deepest sample taken in the gas probes.

In Table 2.2 it can be seen that only 4 (highlighted with red) out of 40 flux measurements showed an emission of methane and also carbon dioxide emissions were low (highest emission was 345 g CO_2 m^{-2} d for 1.1C Oct 07). 11 of the 40 flux measurements had zero carbon dioxide emissions, especially the campaign in January with strong wind and cold weather had low carbon dioxide emission. Only 10 (highlighted with blue) profiles out of the 40 had methane concentrations above 1vol% in the bottom of the profile.

Table 2.3. Ideal and expected load to the biocover windows and possible emission

Raw gas composition[a]	*Methane*[b]	*Carbon dioxide*	*Methane*	*Carbon dioxide*	*Total C*	*CO_2 emission at 100% oxidation*
CH_4/CO_2	g CH_4 m^{-2} d^{-1}	g CO_2 m^{-2} d^{-1}	mole CH_4 m^{-2} d^{-1}	mole CO_2 m^{-2} d^{-1}	mole C m^{-2} d^{-1}	g CO_2 m^{-2} d^{-1}
1.5	150	267	9.4	6.1	15.4	678

[a]Raw gas composition from Task 3.1; Baseline study of methane emission. [b]Methane load determined in Fredenslund et al 2007; Cover Improvement plan

In Table 2.3 the dimensioned and expected load to the biocover windows can be seen The biocover system was dimensioned to receive a load of 150 g CH_4 m^{-2} day^{-1} equaling app 9 mole CH_4 m^{-2} day^{-1}. Assuming the raw gas composition was as found during the baseline study CH_4/CO_2 = 1.5 (average over 9 deep gas wells distributed evenly over the landfill) (see table 2.4) this corresponds to a load of 15.4 mole C m^{-2} day^{-1}m (CH_4 plus CO_2). Looking at the results in table 2.2 this is clearly not reached as only one measurement has a carbon dioxide emission more than 6.1 mole CO_2 m^{-2} day^{-1}, which equals 267 g CO_2 m^{-2} day^{-1} (1.1C on Oct 11th, which is highlighted with red) and the CH_4 emission in this case was negative.

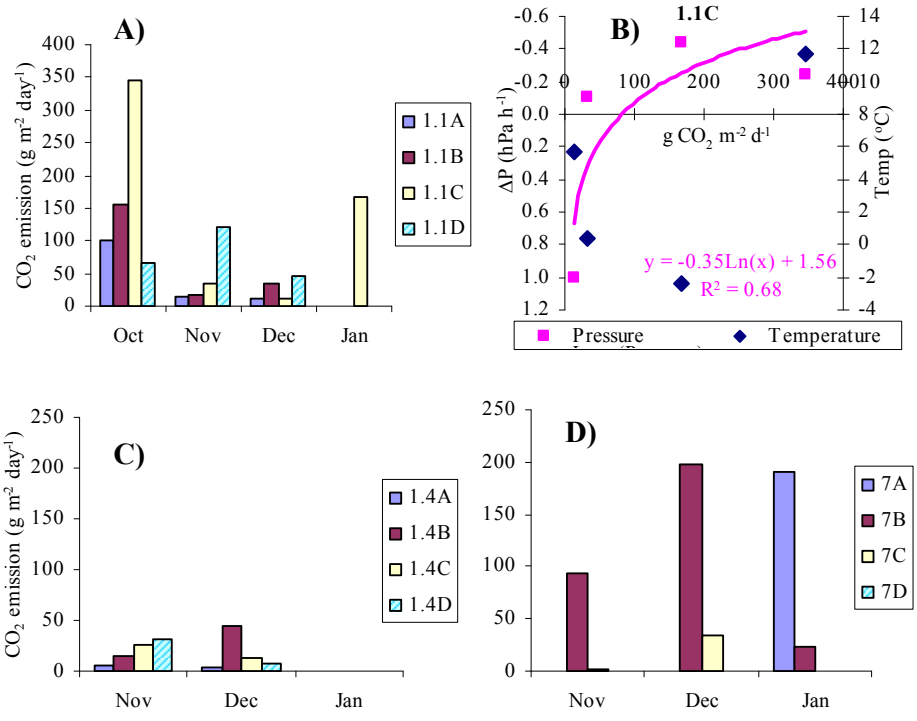


Figure 2.3. A) Emission of carbon dioxide from window 1.1 over the 4 measurement campaigns. B) Emission of carbon dioxide from 1.1C in the 4 campaigns related to temperature and atmospheric pressure change (8am -4pm on the measuring day). C) Emission of carbon dioxide from window 1.4. D) Emission of carbon dioxide from window 7.

Carbon dioxide emissions were very different both spatially and temporarily, which supports the fact that carbon dioxide emission originates from methane oxidation and not from respiration as respiration most be expected to be rather homogenous spatially.

In figure 2.3 the emission of carbon dioxide from 1.1C in the 4 campaigns related to temperature and atmospheric pressure change (8am-4pm on the measuring day) is seen. It was seen that high emissions were related to a decrease in barometric pressure, but also temperature seems to have an impact as the highest emission is seen when there is both a pressure decrease and high temperatures.

In table 2.2 it is seen that only 10 profiles of 40 has methane concentration above 1vol% in the bottom of the profile. In Figure 2.5 ten selected gas concentration profiles can be seen. All profiles except 2 (1.4A and 1.4D Dec 07) were examples of profiles with methane (>1 vol. %) found in the bottom of the profile. In figure 2.5 a profile from the Task 4 report (Pedersen et al 2008) is also showed (lower right) The field profiles were very different from the profiles found in when performance testing the biocover material (Pedersen et. al, 2008). No methane profile is visible, which indicates that the load in the field is lower than what was used in the lab investigation (app 200 g CH_4 m^{-2} d^{-1}) Carbon dioxide was present in all profiles, but it varied between 0.3vol% and 24.4vol% and it is very hard to determine whether the carbon dioxide originates from landfill gas, compost respiration or methane oxidation. In figure 2.4 all 4 profiles taken on window 1.4 on Dec 3 are seen and the CO_2 levels are very different. This could support that the CO_2 originates from methane oxidation and not from respiration, which would be expected to be more stable spatially over the window. The presence of more big branches in one area of the window could explain this, but the high emission areas seem to shift from one part of the window to another so this rules out respiration as a key parameter.

In the gas concentration profiles in figure 2.4 methane oxidation was not evident as very few of them had methane conc. above back ground. It cannot be concluded that all the carbon dioxide that is emitted originates from landfill gas. Some of it could originate from respiration of the compost itself. As very little/no methane is seen in the profile possible methane oxidation must occur lover than the measured profiles. Three deeper profiles were prepared and set down in 1.4 and 1.1 but it was very hard to draw samples from deeper than 1m. Later on it was found that this could be explained by the fact that impermeable waste (clay) was present under both the biocover window 1.1 and 1.4.

The determination of the load by the deep flux chamber measurements were found insufficient and very few stable isotopic measurements were done in this early stage of the project so the only way to determine load and methane oxidation was by using a simple mass balance approach. Though the uncertainties of the influence of respiration of the compost it self can manipulate the results. Therefore it was decided to investigate further the compost respiration in columns not charged with landfill gas, which is presented in Chapter 5. Earlier results from biocover material testing reported in Pedersen et. al, 2008 were evaluated to asses the respiration of a compost column charged with landfill gas, and to evaluate the development of assimilation and respiration as the methanotrophic populations grows over time.

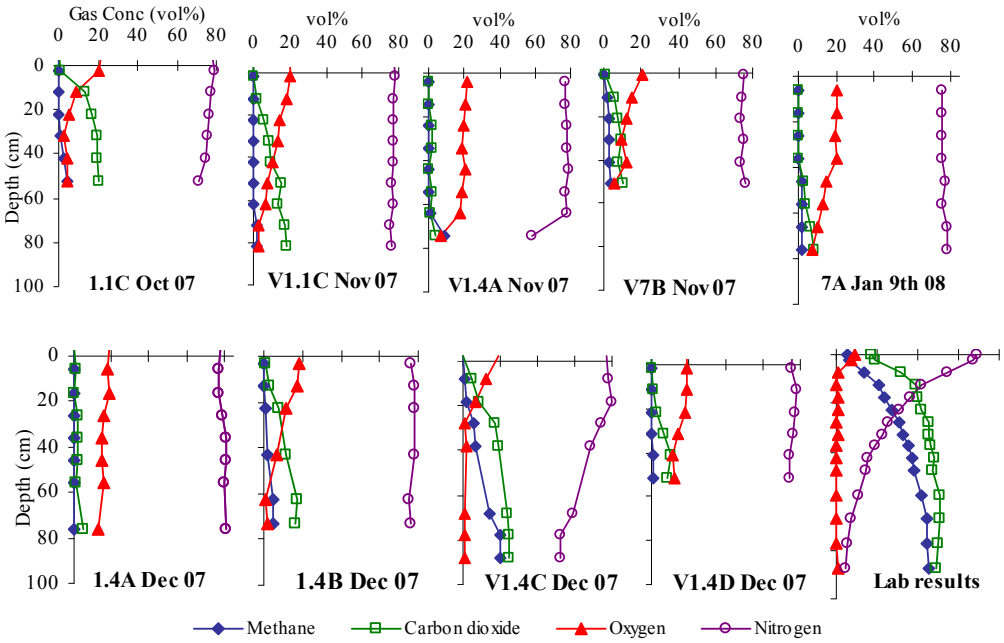


Figure 2.4. Ten selected gas concentration profiles. All profiles except 2 (1.4A and 1.4D Dec 07) are examples of profiles with methane (>1 vol. %) found in the bottom of the profile. All profiles can be seen in appendix 4.

The methane oxidation is quantified by a simple mass balance approach. Steady state is assumed; decay (bacterial respiration) equals growth (assimilation of carbon into biomass) (see appendix 3 for further discussion). Initially no carbon dioxide emission from respiration was subtracted, but values where respiration was subtracted were also presented to be able to see the importance of subtracting the respiration.

Furthermore it is assumed that carbon dioxide do not dissolve in percolating precipitation.

$$J_{D,LFG} - J_{D,CO_2,respiration} = J_{D,CO_2,surface} + J_{D,CH_4,surface} - J_{D,CO_2,respiration} = J_{D,CO_2,bottom} + J_{D,CH_4,bottom}$$

$$J_{D,CH_4,bottom} = \frac{C_{CH_4}}{C_{CH_4} + C_{CO_2}} \cdot \left(J_{D,CO_2,surface} + J_{D,CH_4,surface} - J_{D,CO_2,respiration} \right)$$

$J_{D,LFG}$ is the total flux of landfill gas,

$J_{D,CO2,respiration}$ is the carbon dioxide flux originating from respiration,

$J_{D,CO2,\ surface}$ is the carbon dioxide flux on the surface

$J_{D,CH4,surface}$ is the methane flux on the surface.

The concentration of methane and carbon dioxide can be taken from the bottom of gas concentration profiles or the composition of deeper raw gas samples can be used. Then the total landfill gas flux and the known raw gas composition were used to calculate a load of methane and thereby the loss of methane is determined as the methane oxidized.

The hypothesis that methane oxidation was going on deeper in the gas distribution layer and in the waste itself was followed therefore the methane and carbon dioxide concentrations in deep probes presented in table 2.4 (from Task 3.1) were used to calculate the methane oxidation based on a simple mass balance approach instead of using the conc. found in the bottom of the profile (Last two rows in table 2.2). In Table 2.4 it is chosen to use the average concentration of the raw landfill gas over the entire landfill as the results seem to be quite similar.

Table 2.4. Landfill gas compositions observed in samples from gas probes expressed in percent by volume, methane to carbon dioxide ratio, and excess pressure (Fredenslund et al. 2006)

Probe	***CH_4***	***CO_2***	***O_2***	***N_2***	***CH_4 / CO_2***	P*
	vol. %	vol. %	vol. %	vol. %	mol/mol	mbar
1A	62.7	36.2	0	0	1.7	8.31
1B	57.6	43.5	0	0	1.3	18.84
2B	41.5	32.9	0.8	20.8	1.3	1.23
2C	58.2	31.6	1	5	1.8	0.05
3A	64.7	39.3	0	0	1.6	0.07
3B	61	36	0.4	0	1.7	0.22
3C	63.1	37.9	0	0	1.7	0.05
6A	52.4	39.6	1.1	1.8	1.3	6.95
7A	46.5	30.8	0	18	1.5	0.01
Average	**56.41**	**36.42**	**0.37**	**5.07**	**1.54**	**3.97**
STD dev	**8.03**	**4.16**	**0.47**	**8.32**	**0.20**	**6.44**

*Average values of four measurements of excess pressure for each probe

For the October campaign a methane oxidation rate of 37 g m^{-2} day^{-1} was reached, which is 27% of the initial goal. Clearly the best results were for the October campaign, which had decreasing pressure conditions (-0.24hPa/h) and rather high temperatures (11.7°C). The point 1.1C reaches a methane oxidation rate of 76 g m^{-2} day^{-1} which is 57% of the initial goal. In figure 2.4 the gas concentration profile for 1.1C Oct 07 can be seen, and it can be concluded that most of the methane oxidation is going on below the profile in the gas distribution layer or in the waste.

Table 2.5. Methane oxidized in the 4 initial measurement campaigns based on a simple mass balance, without accounting for respiration.

	Methane oxidized							
	Oct 07	**Nov 07**	**Dec 07**	**Jan 08**	**Oct 07**	**Nov 07**	**Dec 07**	**Jan 08**
	g CH_4 m^{-2} d^{-1}				%			
1.1A	23	3	2	0	100.9	102	101	-65
1.1B	34	4	7	0	100.3	98	100	112
1.1C	76	7	3	37	100.3	95	100	100
1.1D	15	27	10	0	100.1	100	100	100
1.4A		1	1	0		104	100	100
1.4B		3	9	0		100	85	-65
1.4C		6	3	0		100	98	100
1.4D		7	2	0		100	100	100
7A		0	0	-12		-65	-65	-9
7B		20	44	5		90	100	91
7C		0	8	0		116	101	140
7D		0	0	0		78	82	72
Average	**37±28**	**7±8**	**7±8**	**3±12**	**100±0.4**	**85±48**	**84±47**	**65±70**

In Table 2.5 the results for the methane oxidation is seen. The average methane oxidation rate over the 4 campaigns is 9 g m^{-2} day^{-1}, which is 6% of the initial goal (90% of 150 g m^{-2} day^{-1})

To see the influence of accounting for the respiration when calculating the methane oxidation rates this was done for the values in Table 2.5. The respiration found by evaluating data from biocover material performance testing (Pedersen et al 2008) was used. Here an average excess carbon dioxide production of 1.67 mole m^{-2} d^{-1} was found. Respiration was calculated depending on temperature using a Q_{10} value of 3 as Lafleur et al 2005 and Scindbacher et al 2008 reported Q_{10} values from 2.2-4.2 for a temperate peat bog between 5° and 15°. (Temperature dependency is presented in appendix 3) Air temperature was used for the calculation and most likely the temperature in the compost is higher than the air temperature, which will lead to an underestimation of the respiration. Though the results, especially in January, gave negative methane oxidation rates, which could indicate that the respiration was set too high especially at minus degrees (reported Q10 value is not for below 5°C). Therefore it was decided to set the respiration to zero if the temperature was below zero. This resulted in an overall average methane oxidation rate of 6.5 g CH_4 m^{-2} d^{-1} comparable to the 9 g CH_4 m^{-2} d^{-1} which was found not accounting for the respiration.

4 Initial measurement campaigns were done in Oct 07, Nov 07, Dec 07 and Jan 08 on window 1.1, window 1.4 and window 7 on the 12 measuring nests. This added up to 40 flux measurements and gas concentration profiles. Average methane emission was 3.53 g m^{-2} d^{-1} with a standard deviation of 21.7 g m^{-2} d^{-1} (-0.2-137 g m^{-2} d^{-1}). And the average carbon dioxide emission was 45.4 g m^{-2} d^{-1} with a standard deviation of 74.0. Both spatial and temporal variation was significant. Gas profiles showed no methane in 30 out of 40 profiles, but only 1 profile had carbon dioxide conc. under 1vol%. Carbon dioxide could origin from respiration or methane oxidation deeper in the gas distribution layer or the waste.

A rough estimate of the methane oxidation rate was done by a mass balance approach and the results for the 4 campaigns were as follows; 37±28 g CH_4 m^{-2} d^{-1}, 7± 8g CH_4 m^{-2} d^{-1}, 7±8 g CH_4 m^{-2} d^{-1}, 3 ±12 g CH_4 m^{-2} d^{-1}. The average load based on the mass balance approach was 12±29 g CH_4 m^{-2} d^{-1} corresponding to 8% of the initial goal (150 g CH_4 m^{-2} d^{-1}), which made it clear that methane oxidation was limited by the load to the system and therefore it was decided to halt the monthly measurements and try to improve the biocover system.

Conclusion

An initial leak search of the biocover system showed significant leaks around two recirculation wells at unit 1 and the leachate pumping station. Few hotspots were measured on the windows, except on window 7, where 4 hotspots were found. Additionally several hotspots were found on the slope next to window 7, where clay was added to reduce emissions. Subsequently emissions from the pumping station (44.4 kg d^{-1}), recirculation well 1 (20.4 kg d^{-1}) and recirculation well 2 (9.4 kg d^{-1}) was measured by tracer release measurements.

Methane surface emissions measured from the three test biowindows were low and only 4 out of 40 measurements were positive. Mostly neagivel methane fluxes were measured indicating uptake of atmospheric methane of the compost material. Carbon

dioxide emissions ranged from 0 to 347 g m^{-2} day^{-1} with 11 zero emission measurements out of 40. If the initial goal of 150 g CH_4 m^{-2} day^{-1} should be oxidized this would result in a carbon dioxide emission of 678 g CO_2 m^{-2} day^{-1}. Using a simple mass balance approach in the four initial measurement campaigns, an average methane oxidation rate of 9 g m^{-2} day^{-1} with an average load of 12 g m^{-2} day^{-1} was found. The lower than expected methane oxidation rates were believed to be caused by low landfill gas loads to the areas were measurements were done. Two of the four campaigns were done under increasing pressure which seems to severely affect emissions. Under decreasing pressure and a temperature of 12^{o}C a methane oxidation rate of 76 g m^{-2} day^{-1} was measured, which corresponded to 100% oxidation and 56% percent of the initial goal. Therefore it seemed that the methane oxidation potential of the compost is sufficient.

Average methane emission was 3.53 g m^{-2} d^{-1} with a standard deviation of 21.7 g m^{-2} d^{-1} (-0.2-137 g m^{-2} d^{-1}). And the average carbon dioxide emission was 45.4 g m^{-2} d^{-1} with a standard deviation of 74.0. The results show that both temporal and spatial heterogeneity was significant.

Since significant leaks were found and initial performance testing suggested that the landfill gas load to the biocover system was low, improvements of the system to increase load were decided upon.

3 Improvements of biocover system

Initial performance testing of the biocover system suggested that a large part of the Landfill gas was emitting through the leachate collection system, rather than passing through the biocover windows, in spite of measures taken to counter this when constructing the biocover. As described in section 2, capping the leachate wells seemed to prevent the landfill gas from emitting through the top of the wells themselves, but leaking along the edges of the wells was seen. To seal of the edges of the wells, bentonite was added (see figure 3.1). Bentonite was added to all 13 wells fitted with caps in February, 2008. In all approximately 1000 kg of bentonite was used.

Figure 3.1. Leachate well with edge sealed with bentonite.

Capping the leachate wells also seemed to cause a large amount of the gas to emit through a leachate pumping station via the leachate drainage pipes running beneath the deposited waste. This was concluded, since methane screenings showed very high concentrations near and in the pumping station, which was not seen during the baseline study. Tracer measurements during the baseline study also showed that the emission was negligible at that time (Fredenslund et. al, 2006).

Water locks (height = 20 cm) were installed February 2008 on the inlet pipes from the disposal units at the pumping station. Methane screenings after this showed a very effective reduction of landfill gas emission from the pumping station.

In an effort to increase flow of LFG to windows 1.1, 1.2, 1.3 and 1.4, trenches were dug beneath the windows and filled with large tree roots. The trenches were dug in February, 2008 in the middle of each of the 10×10 m windows measuring app. 10 meters long, 1.5 meters wide and 2-4 meters deep. Almost no clay was visible after excavation. The entire windows were not dug out, since dug out waste/soil would have to be deposited elsewhere at an expense for the landfill of app. 700kr/m^3 waste/soil (94 €) - 250 kr/m^3 for digging, transport and re-depositing, and appr. 450 kr/m^3 in loss of income as a lot of the dug out material was soil and not waste (Munk, 2009). For window 1.1 that would result in an expense of app 35.000 €, which could not be justified in relation to the overall budget of the project.

After placing tree roots in the trenches, new compost and gravel was placed in the windows, since the excavated compost and gravel was mixed with clay during excavation. When removing the compost to make the trenches, the gas distribution layers beneath windows 1.1 and 1.2 were seen to contain a lot of water (see figure 3.2), which likely reduced gas flow to the compost material. It is therefore possible that digging the trenches at these locations made gas flux higher both due to higher permeability of the material beneath the windows and drainage of water.

Figure 3.2. Excavation of window 1.2. Water in the gas distribution layer is clearly visible.

Figure 3.3. Excavation of window 1.4. The impermeable clay can clearly be seen in this picture. Furthermore it can be seen how the waste is mixed with clay and it can be seen how close the measuring stations are to the trench.

Two leachate recirculation wells on disposal unit 1, where significant LFG emission was measured during the baseline study, were covered with clay. This was done February, 2008. Thickness of the clay cover was approximately one meter, and the clay soil was compacted to reduce permeability.

4 Biocover performance after improvements

After improvements of the biocover system were completed February 2008, performance testing as described in chapter 2 continued. The results of these measurements are described here. Two campaigns measuring methane fluxes, and soil gas profiles at windows 1.1, 1.4 and 7 were performed after improvements of the biocover system discussed in chapter 3 were done.

A campaign to map spatial variability of methane emissions from Fakse landfill was done. The purpose of this was to identify and assess importance of leaks of the system. This was done by screening the landfill for elevated methane concentrations near the soil surface using a FID as described in section 2, marking the areas, and finally measure methane flux using flux chambers. Also, the spatial variability of landfill gas emission through the biowindows was assessed.

4.1 Performance measurement campaigns

Two measurement campaigns (same as describe in section 2.3) were done after the improvements were done; one in the beginning of April and one in the middle of July.

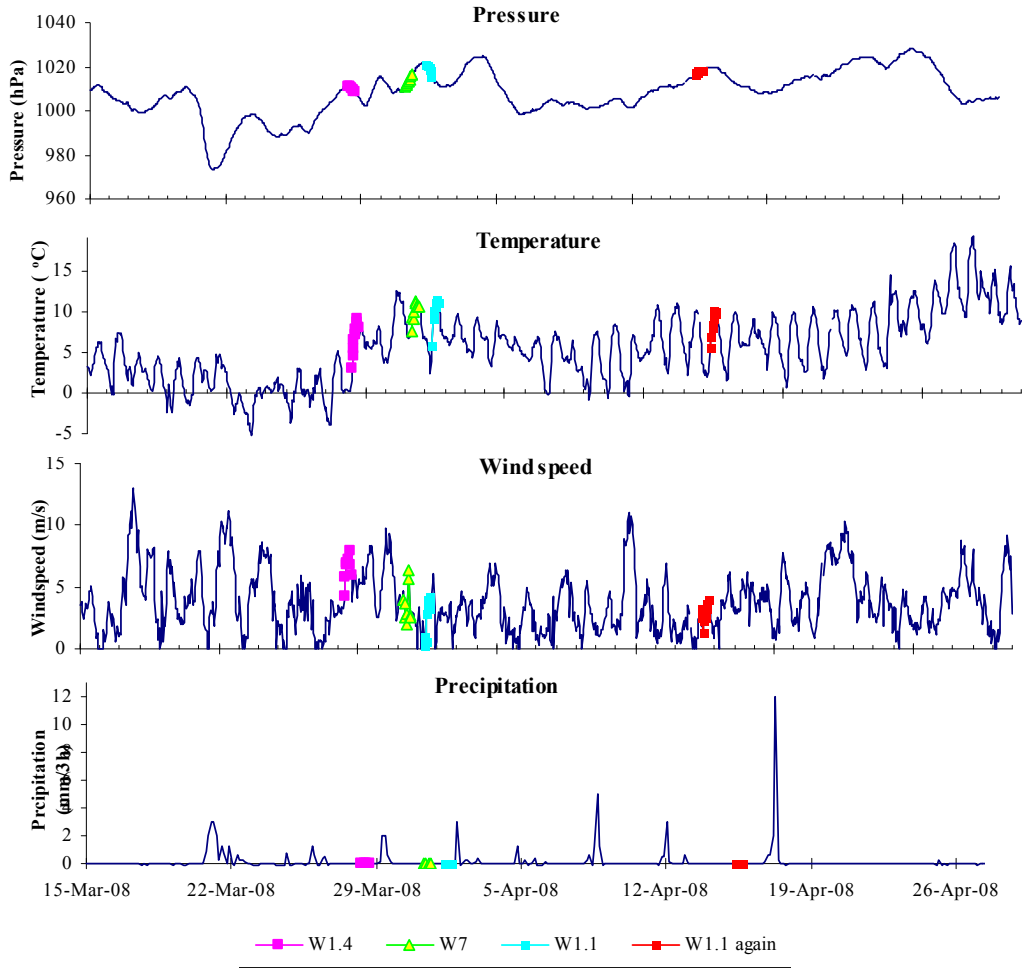


Figure 4.1. Weather conditions under spring and summer campaigns; barometric pressure, temperature, wind speed and precipitation.

Table 4.1: Measurement campaigns and results after the improvement of the biocover system. Hotspots and additional measuring points are presented in italic. Red numbers present indicate carbon dioxide emission above expected load. Green numbers represent zero carbon dioxide emission. Blue numbers indicate methane concentrations above 1vol% in the bottom of the profile.

	Date	ΔP [a]	ΔP [b]	T[c]	Wind Speed[c]	Emissions		Conc.[d]		Methane Oxdised[e]	
						CH_4	CO_2	CH_4	CO_2		
		hPa h^{-1}	hPa h^{-1}	C°	m s^{-1}	g m^{-2} d^{-1}		vol%		g m^{-2} d^{-1}	%
1.1A	April 1st-08	0.47	-0.61	6.7	6.5	-0.11	17.2	0	1.2	3.9	103
1.1B						-0.21	**0.8**	0	0.8	0.3	100
1.1C						0.00	86.8	0.3	2.5	19.2	100
1.1D						0.00	21.6	0	0.1	4.8	100
1.4Bx[f]	March 28th-08	0.36	-0.33	10	3.6	-0.08	10.1	**35**	15.6	2.3	104
1.4C						-0.10	72.9	**1.4**	23.2	16.1	101
1.4D						0.00	21.6	0.1	14.6	4.8	100
1.4 T S						*0.00*	*11.0*	*n.m.*	*n.m.*	*2.4*	*100*
1.4 M						*0.00*	*15.7*	*n.m.*	*n.m.*	*3.5*	*100*
1.4 T N						*-0.06*	*97.6*	*n.m.*	*n.m.*	*21.6*	*100*
7A	March 31st-08	-0.11	0.74	10	2.6	0.10	76.9	0	8.5	17.0	99
7B						0.00	7.4	0.2	6.9	1.6	100
7C						-0.06	8.3	**3.4**	18.5	1.9	103
7D						-0.07	**0.0**	0.0	5.6	0.0	0
1.1Cx[f]	*April 15th-08*	*0.23*	*0.2*	*8.6*	*2.8*	***28.0***	*173*	***29.4***	*27.2*	*27.2*	*49*
1.1X						***560***	*1033*	***53.9***	*30.2*	*8.6*	*2*
1.1A	June 30th-08	-0.02	0.43	17	6.8	-0.3	204	0	10.1	45.2	101
1.1B						0	193	0	21.6	42.6	100
1.1C						86	576	0.6	20.3	93.5	52
1.1D						-0.3	261	0	13.6	57.8	101
1.1M						*-0.1*	*110*	*0.5*	*23*	24.4	100
1.1X						*444*	*1108*	***47.6***	*34.3*	*53,8*	*11*
1.4B	July 9th-08	0.18	0.14	17	4.8	-0.02	**1029**	0.6	10.7	227.4	100
1.4C						-0.01	88	**1.7**	6.6	19.4	100
1.4D						-0.09	110	**2.2**	20	24.2	100
1.4M						*-0.05*	*218*	*0*	*17.2*	*48.1*	*100*
HS1						***31.68***	***974***	*n.m.*	*n.m.*	*202.8*	*86*
HS2						*-0.11*	*470*	*n.m.*	*n.m.*	*104.0*	*100*
HS3						***49.08***	*985*	*n.m.*	*n.m.*	*198.5*	*80*
7A	July 10th-08	0.14	-0.13	18	4.6	0.07	131	0.1	12.4	29.0	100
7B						-0.16	245	**1.1**	19.7	54.2	100
7C						0.14	**659**	**2.2**	22	145.7	100
7D						-0.13	115	0.1	12.5	25.5	101
HS V7A						*-0.13*	***321***	*n.m.*	*n.m.*	*71.1*	*100*
HS V7B						*0.09*	*186*	*n.m.*	*n.m.*	*41.0*	*100*
HS1						***2.95***	***895***	*n.m.*	*n.m.*	*196.5*	*99*
HS2						***253***	***3784***	*n.m.*	*n.m.*	***736.9***	*74*
HS3						***260***	***3021***	*n.m.*	*n.m.*	***565.5***	*69*
1.1A	July 15th -08	0.20	-0.21	19	7.1	n.m.	n.m.	0	14.9		
1.1B						-1.17	220	0.2	21.2	49.2	102
1.1C						-0.08	147	0	16.5	32.5	100
1.1D						-0.09	249	0	19.3	55.0	100
1.1M						*0.06*	***449***	***5.5***	*23.5*	*99.2*	*100*
1.1X						***768.80***	***2289***	***49.5***	*36.5*	*204.3*	*21*

[a] The pressure gradient 24h before the measuring campaign (8am to 8am) [b]The pressure gradient over the measuring day from 8am to 4pm. [c]Average between 8am-4pm. [d] Concentration in the deepest sample taken in the gas probes. . [e]Methane oxidation rates are calculated without subtracting the respiration [f] The 1.4Bx and 1.1Cx are longer probes (2m) set down next to the original probes. Hotspot and additional points are presented in italic

In Table 4.1 the measurement campaigns and results after the improvement of the biocover system can be seen. Some additional points (hot spots and points directly on the trench) were measured (see figure 4.2), as it was now clear that all measuring

nests on window 1.1 and window 1.4 were placed on top of a heavy clay layer. The aim was that the gas would spread vertically from the trench area and thereby activate a bigger part of the biocover window than the area right above the trench.

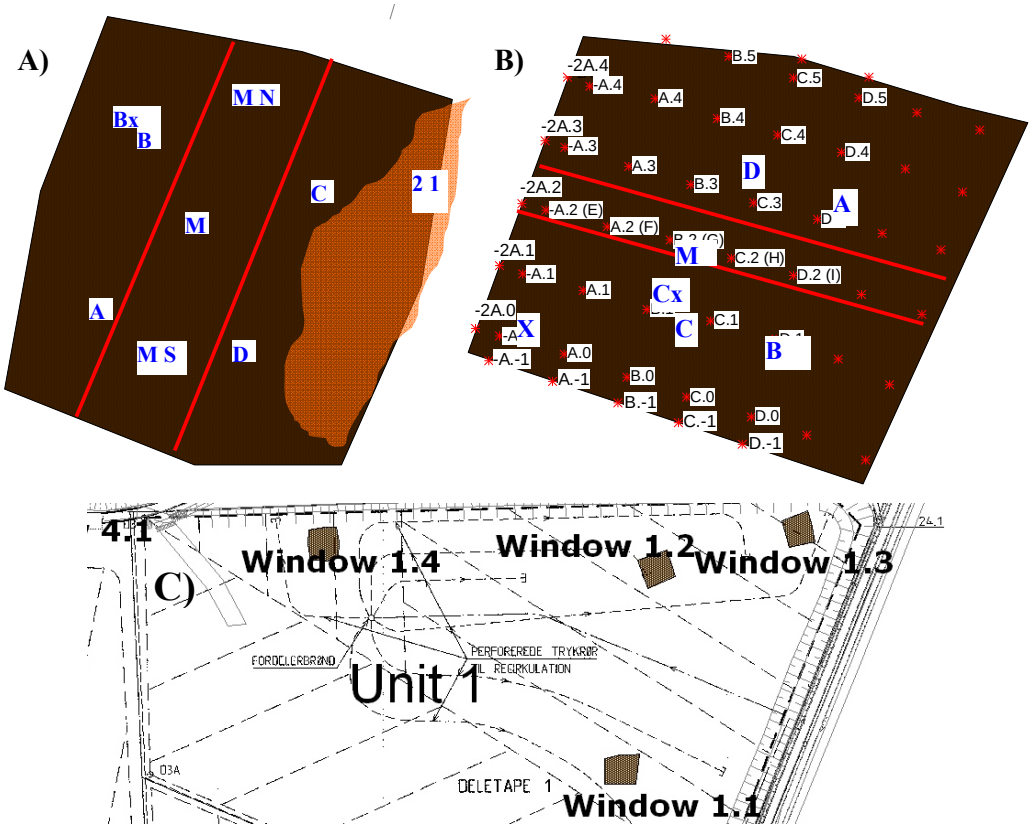


Figure 4.2. A) Window 1.4, original measuring points; A, B, C and D and additional measuring points; Bx, MN, M, MS and hotspots 1,2 and 3. B) Window 1.1 with original measuring points A, B, C and D and additional measuring points; X, Cx and M. C) Zoom of unit 1 with the location of the biocover windows, the leachate system and the leachate recirculation system. The leachate recirculation pipes are placed ½-1m under the top of the waste with +/- 1m uncertainty. The certainty on the windows is 2-3cm.

The results in the end of March, beginning of April show no improvement in the load to the biocover window. Though it can be seen in Table 4.1 that increasing pressure were seen 24h prior to the measurements done both on window 1.1 (ΔP=0.47hPa h^{-1}) and window 1.4 (ΔP=0.36hPa h^{-1}). In figure 4.1 it can also be seen that 2 weeks leading up to the first measurement day (28th of Marts, window 1.4) the pressure was increasing from 974 hPa to 1009 hPa, which can question how representative the results obtained in this campaign will be. For all 3 measuring days in March April no methane emissions were seen and the carbon dioxide emissions were all below 100 g m^{-2} day^{-1} (app. 1/7 of the initial goal for the load). Furthermore two examples of zero emission carbon dioxide were presented. For the March campaign at window 1.4, 3 measuring points were added on top of the trench (see figure 4.2), but emissions were not higher above the trench, than seen on the original measuring points. According to these results the digging of the trench in window 1.4 did not improve the gas flow to the window. Though results presented in Chapter 6.1, indicates that improvement has

been achieved on window 1.1 and also emissions on window 7 were clearly seen where trenches were made to improve the gas flow to the windows.

After interviewing an old landfill employee it was found that in the old part of the landfill (unit 1) the practice was to cover the deposited waste with clay after each working day and therefore the waste probably is encapsulated in several clay pockets. This can most likely explain the difficulties controlling the landfill gas and achieve a vertical gas flow through the windows. When attempting to install a leachate recirculation system at unit 1, it was found that recirculated leachate would not percolate through the upper waste layer but run of as surface water (Houe, 2009), which gives an idea of how impermeable the upper waste layers in the landfill are. Though the leachate collection system has contact to a lot of these clay pockets and it is seen that the leachate collection system continuously has high emissions (see FID screening in the next chapter) even that a variety of initiatives have been done in order to avoid this.

In Table 4.1 the concentrations in the deepest sample taken in the gas probes was also presented. For the March April campaign only 3 of the 11 points had methane concentrations above 1vol%. Even one of them was the point 1.4Bx, which was a slightly deeper probe (1.5m depth) set down 50cm west of 1.4B (se figure 4.2A)) and the sample presented in Table 4.1 was taken in 1.3m depths and the probe was placed closer to the edge of the biocover window (Origin of the load to the biowindow).

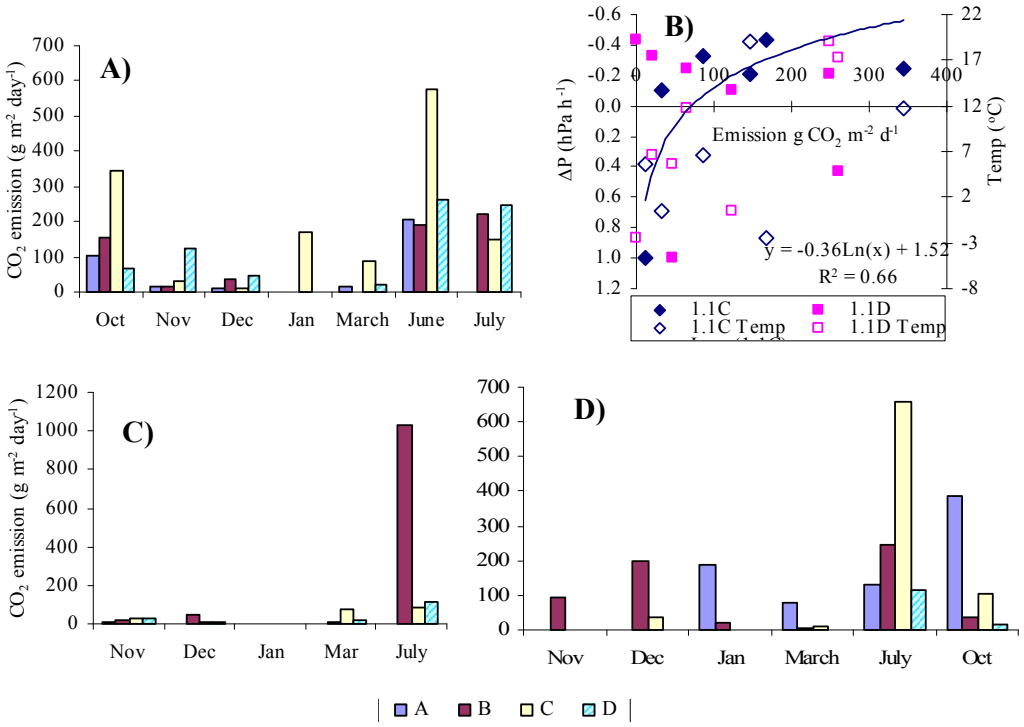


Figure 4.3. A) Emission of carbon dioxide from window 1.1. B) Emission of carbon dioxide related to atmospheric pressure and temperature for point 1.1C and 1.1D. The trend line is the relation between change in atmospheric pressure and emissions from 1.1C. C) Emission of carbon dioxide from window 1.4. D) Emission of carbon dioxide from window 7.

In Figure 4.3 it can be seen how emission increased from April to June/July campaigns, but it was not clear whether the improvements of the system done in February had a significant effect. One possible reason for the improvement of the load to the biocover windows from March to July was that the gas distribution most likely will be dryer in June/July and thereby the gas permeability of the gas distribution system was higher and a bigger part of gas will therefore escape through the biocover windows. Furthermore the leachate recirculation system will be dryer, which is suspected to provide a large fraction of the load to window 1.1 and window 1.4. In figure 4.2C is shown a zoom of unit 1 with the location of the biocover windows, the leachate system and the leachate recirculation system. The leachate recirculation pipes are placed ½-1m under the top of the waste with +/- 1m uncertainty (Houe, 2009). The recirculation system was not connected to the rest of the leachate system, but the pipes (ordinary leachate system and recirculation) could be very close in the north-western part of the landfill, where the landfill body is shallow. In the figure it can be seen that the recirculation system pipes are very close to the hotspots on window 1.1 (SW corner, point X) and also close to the eastern part of 1.4 where the hotspot is located. Also, elevated emission of CO_2 was seen from 1.4B NW corner, which could originate from the recirculation pipe on the other side of window 1.4.

In figure 4.3B) Emission of carbon dioxide related to atmospheric pressure and temperature for point 1.1C and 1.1D can be seen. The trend line is the relation between change of atmospheric pressure and emissions from 1.1C with an R^2 value of 0.66, which did indicate a relation. The relation with temperature was less obvious for 1.1C (R^2=0.33), which does imply that the carbon dioxide emission from 1.1C is controlled by the load of landfill gas and not methane oxidation or respiration, which are dependent on temperature. For 1.1D the opposite seems to be the case. The carbon dioxide emission depends more on temperature (R^2=0.62) than on barometric pressure (R^2=0.03).

In figure 4.4 the gas concentration profiles obtained in the hotspot area of window 1.1(X) is presented. It shows that the difference in the load over time is very significant. On April 1st no methane was seen in the profile and on April 15th the hotspot was overloaded with hardly no oxygen diffusing into the compost matrix. In figure the gas concentration profiles in July for the 4 measuring points on window 1.4 and on window 7 can be seen. The profiles correspond well with the emission data in table 4.1. Point 1.4B is the point with the highest emission of carbon dioxide (1029 g m^{-2} day^{-1}), which is actually higher than the expected emission (678 g m^{-2} day^{-1}) at 100% oxidation of expected load. The profile at 1.4B is also the one with the lowest penetration of oxygen and the highest carbon dioxide concentrations.

In window 7 the point with the highest carbon dioxide emission is point 7C(659 g CO_2 m^{-2} day^{-1}, 0.14 g CH_4 m^{-2} day^{-1}), which also corresponds well with the profile for 7C seen in figure 4.4.

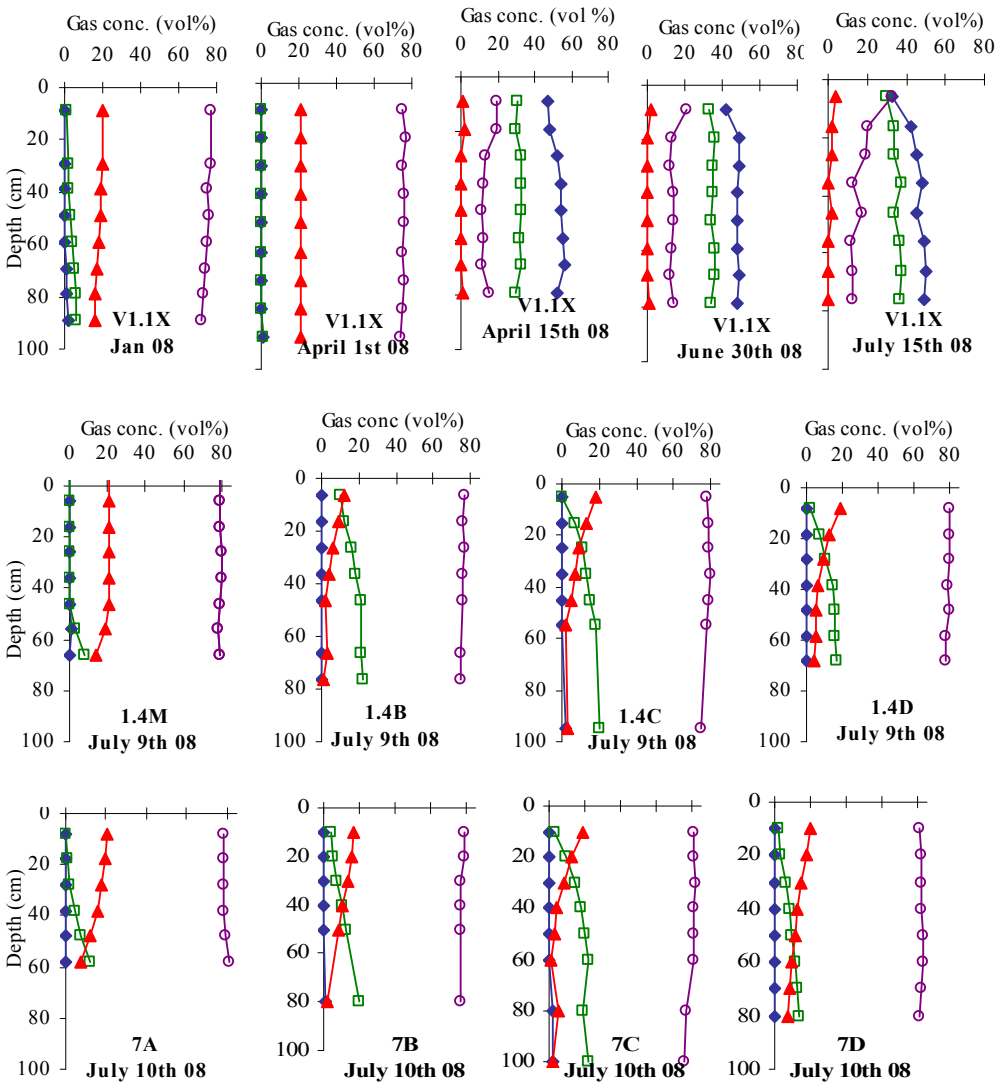


Figure 4.4. Gas concentration profiles for the 4 measuring points on window 1.4 and on window 7.

In the right column of Table 4.1 the methane oxidation rates are shown (calculated using the mass balance approach as seen in chapter 2). The overall average methane oxidation rate is 88 g m^{-2} day^{-1} for all the emission measurements. Subtracting the temperature dependent respiration the number is 80 g m^{-2} day^{-1}, so here it seems that the respiration is not that important. To be able to compare the average methane oxidation rate with the previous campaigns the average methane oxidation rate is calculated for both campaigns without counting the hotspots as it is assumed that they have been there all a long. For the March campaign this gives 6.5 g m^{-2} day^{-1} (7.1 with the hotspots). For the July campaign the result is 64.6 g m^{-2} day^{-1} (149 g m^{-2} day^{-1} with the hotspots), which is actually the exact dimensioned load to the biocover windows. Subtracting the respiration the numbers are 54.7 g m^{-2} $day^{-1}$and 138 g m^{-2} day^{-1} respectively. Though some of the methane oxidation rates for the hotspots seem unrealistically high, 736 g m^{-2} day^{-1} and 565 g m^{-2} day^{-1} are estimated for the hotspots in window 7 in July but this method accounts also for methane oxidation going on in

the waste under low emission periods and in low emission areas, which continuously changes the gas composition. Looking at the profiles where no landfill gas was emitted (figure 4.4) it can be seen that oxygen diffuses all the way to the bottom of the biocover easily as the compost material is very permeable. Therefore the oxidation in the waste was assumed to be increased by the biocover windows as they allow for oxygen to diffuse into the landfill body. Though the elevated carbon dioxide can also origin from aerobic degradation of the waste, similar to the respiration from the compost it self. For window 7 very high methane oxidation rates were seen and low methane concentrations (46 vol. %) was also observed in the deep probe 7A (confer Table 2.3). A raw gas concentration of 56 vol. % methane has been used to calculate the methane oxidation. Calculating the rates with the lower raw gas composition gives rates at the hotspot of 727 g m^{-2} day^{-1} and 557 g m^{-2} day^{-1}. In appendix 5 a FID screening for window 7 on July 10th are seen. This FID screening is used to assign areas to the methane oxidation rate and thereby calculate a total methane oxidation rate for the window on that specific day.

There is one major hotspot (5m x 9m) between V7A and V7B in the western side of the window close to the slope. Three points were chosen for flux measurements. For window 1.4, 3 points were also chosen to describe the hotspot on the window. The calculated methane oxidation rates are subtracted the compost respiration found in Chapter 5 "Investigation of compost respiration", (2.8 mole m^{-2} day^{-1} as a fairly conservative estimate).

Table 4.2. Methane emission and estimated oxidation.

	Average CH_4 Emission	***Assigned area***	***Total CH_4 emission***	***Average CH_4 oxidation rates***	***Total CH_4 oxidised***
	g m^{-2} d^{-1}	m^2	kg day^{-1}	g m^{-2} d^{-1}	kg day^{-1}
Remaining area	-0.02	1434	-0.03	45.5	65.2
Higher emission hotspot 7A	-0.1	13.5	0.00	53.0	0.7
Low emission hotspot 7B	0.1	15	0.00	22.9	0.3
High emission hotspots (2)	171.84	67.5	11.60	481.5	32.5
Total window 7 July 10th 2008			**11.6**	**64.5**	**98.8**
Remaining area	-0.04	69.1	0.00	63.9	4.4
Hotspot 1.4 east	26.88	10	0.27	152.6	1.5
Total window 1.4 July 9th 2008			**0.3**	**75.2**	**5.9**
Hotspot 1.1 west	133.6[a]	49	6.54	86.7	4.2
Remaining area	21.4	41	0.88	43.0	1.8
Total window 1.1 June 30th 2008			**7.4**	**65.1**	**6.0**
Total for all 3 windows			**19.3**	**65.1**	**110.7**

[a]This average is based on a Surfer elaboration with 24 flux measurements done on window 1.1 the 30th of June.

In table 4.2 the estimates of methane oxidation for the July campaign is seen. The total amount of methane oxidized was 111 kg $day^{-1,}$ which corresponds to 15% of the total emission from the baseline study. Assuming the average methane oxidation rate on all implemented biocover windows this will result in an oxidation of 43% on this specific day. Though this estimate is probably not conservative enough as the 3 investigated windows seem to be the windows with the highest load (based on FID emission screenings). Therefore it is likely that the true estimate is in between the two

numbers (15%-43%). Furthermore the results are based on a warm summer day and lower methane oxidation most be expected during the winter.

On April 1st 2008 one set of samples (1.1C) was subjected to an analysis for stable isotopes. The stable isotopic method is based on the fact that the bacteria prefer the C^{12} over the C^{13} carbon isotope, and by knowing the rate by which they do this and the stable isotope composition for the anaerobic zone, the percent oxidation in a point z, can be determined ($f_{ox,z}$).

$$f_{oxo,z} = \frac{\delta_z - \delta_A}{\alpha_{ox} - \alpha_{trans}} \cdot 0.1 \qquad \text{(Chanton \& Liptay 2000)}$$

$$\alpha_{ox} = -0.00039 \cdot T + 1.0421$$

δ_E is the $\delta^{13}C$ value for the emitted methane and δ_A is the value for the anoxic methane. The α_{ox} is the degree of isotopic fractionation done by the specific microbial population under specific conditions. This fractionation factor can be determined from a batch experiment. The α_{trans} value is isotope fractionation factor due to transport, which can be set to 1 for purely advective systems. If diffusion affecting the system this will cause an underestimation (Chanton et al 2008b).

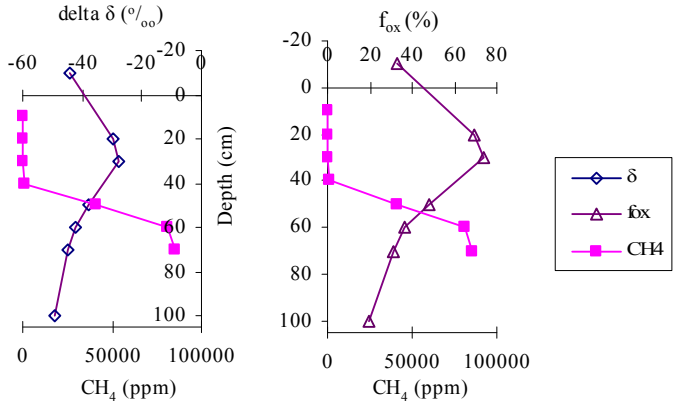


Figure 4.5. Stable isotope results for 1.1C April 1st 2008. The results above the ground are average over 3 measurements in the surface flux chamber. The result in 100cm is the result from the deep flux chamber.

The results show that the methane was already oxidized by 20% before reaching the biocover window, which supports the assumption that the methane is oxidized in the gas distribution system and in the waste itself. Furthermore it can be seen that the highest value was seen in app 30cm depth (80%), which is in correspondence with results reported by Chanton et al 2008a. The author suggest to use and average between the oxidation found in the oxidation zone and the oxidation found in the surface flux chamber, which in this case will result in app. 50% oxidation. Though the fact that hardly any emission of methane is present results in an under estimation as totally oxidized methane is no accounted for, therefore it is believed that the 80% oxidation is actually the closest to the actual result in this very case. Furthermore the results correspond well with the fact that the method normally gives lower values than the mass balance approach. The results above the ground are average over 3

measurements in the surface flux chamber. The result in 100 cm is the result from the deep flux chamber.

Screening of methane surface concentrations

To qualitatively access the overall emission pattern from the biocover windows and expected escape routes, a FID screening was done on April 15th 2008 (see weather condition in Table 4.1). The general picture was that hotspots with methane emission were present on almost all biocover windows especially along the edges of the windows. This indicates that the load is coming from the sides of the windows through the gas distribution layer, meaning that the goal of getting in contact with the landfill body beneath the biocover windows is not reached. Also, high concentrations were still measured around recirculation wells and the pump station.

Table 4.5. Observations from surface screenings of methane concentrations

Location	*Conc.*	*Location*	*Conc.*	*Location*	*Conc.*	*Location*	*Area*
	ppm		ppm		ppm		m^2
Window 1.1	2455	1.1X	1800	-A.0	1400	A.0	6
Window 1.1	160	B.0	25	C.0	15	D.0	6
Window 1.1	b.g	E.0	190	1.1C	800	1.1Cx	10
Window 1.1	400	-A.1	300	A.2			5
Window 2 HS 1	400	1m from SE edge	40	3m from SE edge	10	5m from SE edge	50
Window 2 HS 2	20	1m from SW edge					1
Window 2 HS 3	5	1m from SW edge					1
Window 1.2	b.g						-
Window 1.3	b.g.						-
Window 1.4 HS	600	SE edge					20
Window 3	b.g.						-
Window 4.1	30	Entire window					336
Window 4.2	b.g						-
Window 6	1100		500				10
Window 7	4	Around 7A					4
Recirculation well R1	300	On clay covering					
Recirculation well R2	1100	On the clay covering	300	15cm from the clay covering			
Leachate well D8	300	Edge of well	300	30cm from bentonite	70ppm	½m from bentonite	
Leachate well D2	>2500	On the bentonite	2000	30cm from bentonite			
Pump station	>2500	Well cell 1	>2500	Another well	700	Another well	
Pump station	40	Another well	20	Another well	20	Big pump station	

In table 4.5. it can be seen that an appr. area of 550m^2 (10% of the entire area) of the windows has methane emission on this specific day. Based on these results the load to the biocover windows is not so bad.

4.2 Spatial variability in emissions

To evaluate leaks of the system, a campaign was performed to map methane emissions from the site. This involved screening of the entire soil surface of the landfill, and all biowindows. Also surface emission through soil near leachate wells

was in focus, since earlier screenings suggested high emissions at these locations. Upon locating emission hot spots, the area of each hot spot was measured, and flux measurements were performed to assess methane emission rates, and thereby identifying important leaks of the biocover system.

Soil cover and biocover windows

The soil cover was screened by measuring methane concentration near the surface of the soil cover and surface of the biocover windows using a portable FID. The entire surface of section I was screened crossing the landfill with 10-20 meter intervals. When methane concentrations above background level were observed, the highest concentration of the area (hot spot) was noted, and the approximate area was measured by screening the surface using the FID, locating the borders of the emission area.

Table 4.6. Highest methane concentrations observed and approximate areas of methane emission hot spots found by FID screening of Fakse landfill section I October 29 and 30, 2008.

Disposal unit	Location	Area (m^2)	Highest observed methane concentration (ppm)
1	Soil surface near old sludge disposal site	4	20
	Window 1.1 hot spot	80	>3000
	Window 1.3 hot spot	1	130
2	Window 2 hot spot	30	70
	Soil surface north of window 2	25	50
4	Window 4.1 hot spot	45	300
5	Soil surface, 3 small hot spots	12	70
6	Window 6, 4 hot spots	60	>3000
7	Window 7, 4 hot spots	161	>3000
	Soil cover, steep slope near window 7	180	>3000

With the exception of the slope on unit 7, emission through the soil seemed to be low. The concentration screening listed in table 4.6 suggested that more methane emitted through hot spots on the biocover windows, where the methane load was higher than the methane oxidation capacity of the biocover material. The combined area of the found hot spots on the biocover windows was approx. 250 m^2 compared to a total area of the windows of 5000 m^2.

Using a portable flux chamber coupled with the Innova photoacoustic detector, methane and carbon dioxide fluxes were measured on the found hot spots both on the soil surface and biocover windows. The number of flux measurements per hot spot varied between one on each of the smallest hot spots and seven for the largest one. At window 1.1, where a more detailed study was made, approximately 50 flux measurements were done on the 100 m^2 biocover window. In all, 108 flux measurements were made. By multiplying the average flux with the measured area, emission rates were found for each hot spot.

Table 4.7. Methane emissions from hot spots on the soil surface and biocover windows on section I of Fakse landfill measured October, 2008

Disposal unit	Location	Area (m^2)	Methane emission (kg CH_4 d^{-1})
1	Soil surface near old sludge disposal site	4	0.0
	Window 1.1 hot spot	80	29.8*
	Window 1.3 hot spot	1	0.02
2	Window 2 hot spot	30	0.2
	Soil surface north of window 2	25	5.5
4	Window 4.1 hot spot	45	0.4
5	Soil surface, 3 small hot spots	12	0.0
6	Window 6, 4 hot spots	60	5.0
7	Window 7, 4 hot spots	161	11.7
	Soil cover, steep slope near window 7	180	29.0
		Sum	**81.6**

* Flux of window 1.1 was measured December 1, 2008

The flux measurements show that the methane flux through the surface of the landfill occurred mostly through the biocover windows, rather than through the soil cover, with the exception of a steep slope on disposal unit 7. The low emission through the soil cover is most likely due to a low permeability of the soil used.

The total area of the hot spots on the biocover windows was found to be approximately 380 m^2, whereas the total area of biocover windows was 5000 m^2. This suggests that landfill gas is distributed unevenly to the biocover windows. The methane emission measured on window 1.1 (see table 4.7) was higher than the anticipated load to the filter (15 kg CH_4 d^{-1}). Possible reasons for this are discussed in section 7.

Leachate wells

Methane emission through the soil surface surrounding many of the leachate wells after installation of caps was observed from initial screenings. To quantify this emission, screenings and flux measurements were made during the same measurement campaign were other emissions through soil and biocover windows were measured described in the previous section.

At each well, methane concentrations near the soil surface was measured using FID. Concentrations were recorded at the edge of each well, 1 meter from each well, and two meters from each well. Depending on the significance of the emission evaluated by screening, between two and six flux measurements were made around each well (all results are presented in Appendix 6). Equipment used for flux measurements was the portable flux chamber coupled with an a FID detector to measure methane concentration and a Vaisala NDIR detector to measure concentration of carbon dioxide. Locations of flux measurements and methane concentrations were noted. An example of these results is illustrated in figure 4.4. To calculate methane emission from each well, average fluxes were multiplied with areas. Example: We have one flux measurement within 1 meter (0.6 kg m^2 d^{-1}), and two between 1 and 2 meter (0.4 and 0.1 kg CH_4 m^{-2} d^{-1}). Total emission from the well is then estimated as:

0.6 kg CH_4 m^{-2} d^{-1} * 7.7 m^2 + (0.4 + 0.1)/2 kg CH_4 m^{-2} d^{-1}* 14.0 m^2 = 8.1 kg CH_4 d^{-1}

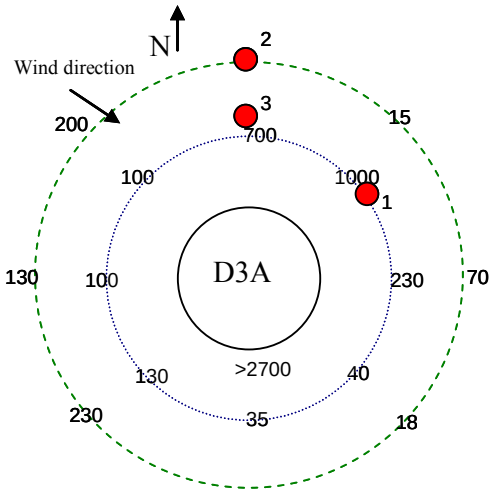


Figure 4.4. Example of methane screening results and location of flux measurements from the surface near a leachate well. Concentration unit is ppmv. (all results are presented in appendix 6)

In a two cases, where methane emission was found during concentration screening, methane flux was not measured due to technical difficulties at these locations. Also, during screening leaks in some of the caps were found. This means that landfill gas was emitting through some of the caps at the time. These leaks were not measured, since the flux chamber setup cannot be used for these measurements.

Using the described method, methane emission from soil surface near seven leachate wells was measured:

Table 4.8. Methane emission through soil near leachate wells.

Well	**CH4 emission (kg d^{-1})**
D2	1.3
D3A	11.3
D6	0.0
D10	14.2
D12	6.5
D13	0.1
D15	6.6
Total	40.0

As seen in table 4.8, 40 kg d^{-1} was found to be emitting from the soil near leachate wells. This is a significant emission compared to measurements of total methane emission from section I before installation of biocover: 740 kg CH_4 d^{-1} (Fredenslund et. al, 2006).

The total emission through the leachate system was most likely considerably higher than 40 kg d^{-1}, since methane emitting from leaks in the caps was not measured, and flux measurements at two locations were not done.

In figure 4.5, methane emissions measured during the October, 2008 campaign is shown on a map over Fakse landfill. Both emissions from surface surrounding leachate wells, as well as the emissions through biocover windows and soil cover is shown.

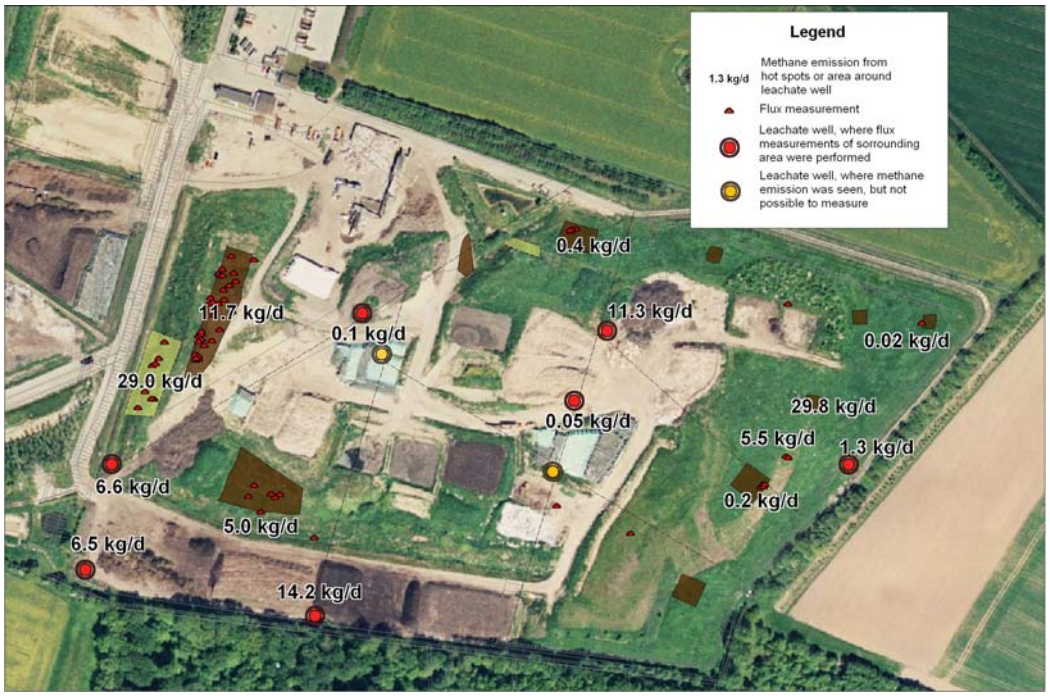


Figure 4.5. Methane surface emissions from soil cover, near leachate wells and biocover windows.

Most methane was found to be emitting near leachate wells or through biowindows, with the exception of the steep slope of the soil cover near window 7. High emissions were also found near leachate wells, and since the measurements to a large extend does not account for all methane emitting through the leachate wells, it is concluded that the leachate system remained a significant pathway for landfill gas emission from the site in spite of several initiatives to reduce it.

5 Compost respiration

Initial field measurements of methane and carbon dioxide emissions from the installed biocover windows at Fakse landfill had shown high carbon dioxide emissions and no methane emissions indicating significant methane oxidation in the compost material placed in the biowindows. However, gas concentration profiles measured in the compost windows often showed elevated carbon dioxide concentrations throughout the compost covers, but no methane not even in the deepest gas probes (100 cm below surface). Based on these observations two hypothesis were possible; either all the methane going to the biowindow was oxidized in the gas distribution layer beneath the compost layer, or the methane load to the biowindow was insignificant and the measured carbon dioxide emissions solely a result of respiration of the compost material itself.

The objective of this task was to quantify compost respiration in terms of oxygen consumption and carbon dioxide production and emission rates. Oxygen consumption and carbon dioxide production rates were measured in batch incubation experiments containing compost. Furthermore, methane oxidation rates, carbon assimilation and the contribution of carbon dioxide production from respiration during methane oxidation were determined. Compost for batch incubation was sampled from two different methane emission areas in window 1.1 at Fakse landfill; a high and a medium emission area. Carbon dioxide production and emission rates were determined in column studies simulating a compost biocover where oxygen from the atmospheric air is diffusion into the compost layer. Column gas concentration profiles were compared to field measurements. Based on the carbon dioxide rates obtained from the column studies an overall emission rate for the whole window was calculated.

Methodology

The compost material for the laboratory experiments was sampled at biowindow 1.1 (Section 1, Unit 1) at Fakse landfill. The window consists of a 10 cm gravel layer for gas distribution on top a 1m layer of 4 years old non-sieved raw compost (referred to as RC4 in Pedersen et al., 2008). The compost material was tested for methan oxidation capacity and oxygen consumption due to respiration in the Biocover task 4. The results concluded that its low cost, low respiration rate and high methane oxidation capacity made it the best choice for the cover layer of the biowindows at the Fakse landfill. Table 5.1 provides an overview of the results of the initial testing of the raw compost in terms of methan oxidation potentials and oxygen consumption. The results of the initial material tests are described in detail in Pedersen et al. (2008). Compost samples for batch incubation tests were taken at two hotspots in the compost window showing high surface emissions. Compost sample called HHS was dug out from the highest emission hotspot (532 g CO_2 m^{-2} day^{-1} and 113 g CH_4 m^{-2} day^{-1}) whereas the other sampling point HS was placed in a medium emission area (632 g CO_2 m^{-2} day^{-1} of and 59 g CH_4 m^{-2} day^{-1}). The compost materials tested in the experiments were sampled from the upper oxic part of the compost layer (10-20 cm depth).

Table 5.1. Characteristics in terms of methan oxidation potential and oxygen consumption of the compost material used in the biowindows installed at Fakse landfill (Pedersen et al., 2008). The compost material was tested in batch and column experiments.

Raw compost 4 years (RC4)			
Water content		per 100 g DM	71.9±1.5
Potential methane oxidation rate in 3 subsequent batch experiments	1	μg CH_4 g dry $soil^{-1}$ $hour^{-1}$	53.4±14.9
	2	μg CH_4 g dry $soil^{-1}$ $hour^{-1}$	74.9±1.3
	3	μg CH_4 g dry $soil^{-1}$ $hour^{-1}$	160.8±2.4
Oxygen demand		μg CH_4 g dry $soil^{-1}$ $hour^{-1}$	3.8±2.1
Methane production		μg O_2 g dry $soil^{-1}$ $hour^{-1}$	0.0
Bulk density		kg m^{-3}	486.61
Column methane oxidation rate	Maximum	g m^{-2} day^{-1}	147
		%	75
	Average	g m^{-2} day^{-1}	108±20
		%	55±10
	Day 111	g m^{-2} day^{-1}	76
		%	39

Batch experiments

Methane oxidation rates and oxygen consumption rates were determined in batch incubation experiments containing compost material. A fixed amount of material (100 g moist material) was amended to a 1000 mL glass incubation bottles equipped with butyl rubber septum (8 mm thick) held in place by alumina screw caps. The septum enabled gas to be sampled or injected by a hypodermic needle and a syringe. In the respiration tests, the bottles contained atmospheric air. To obtain CH_4 oxidizing conditions, air was withdrawn from each container using a syringe and replaced with CH_4 and O_2, which gave an initial mixture of CH_4 (15 %vol.), O_2 (35 %vol.) and nitrogen (N_2) (50 %vol.). The batch experiments were all carried out in duplicate at room temperature (22°C).

In order to check if any disappearance could be due to non-microbial processes (abiotic degradation, sorption and volatilization) deactivated control batches with sterilized coarse (100 g) and were conducted. Controls were sterilized by autoclaving (three times for 1 hour at 121 °C).

The main gas components (CH_4, CO_2, O_2, and N_2) were analyzed on a Chrompack Micro GC CP-2002P GC equipped with a thermal conductivity detector and two columns. O_2 and N_2 were quantified on a 4 m long Molsieve 5A column and CH_4 and CO_2 on a 10 m long Poraplot Q column. Carrier gas was helium, and the column temperature was 40°C. The Micro GC is equipped with a sample loop injection unit containing a syringe which enables direct sampling from the test bottles. Gas standards (MicroLab, Aarhus, Denmark) ranging from 0.02 to 50 % vol. were used for calibration.

Maximal consumption/production rates and regression coefficients (R^2) were obtained from fitting the experimental data to a zero-order reaction process. The zero order rate-constant was normalized to the dry compost mass.

Column experiments

The column setup consisted of three columns including one control column containing sterilized sand and two columns containing compost from biowindow 1.1. The compost material was sampled from a trench that was dug out of the window. The compost material was mixed before it was placed in the columns. The experimental columns consisted of PVC column closed at both ends with PVC caps fitted with rubber O-rings. The columns were 1 meter high, with an inner diameter of 0.2 meters. The column experiments had a continuous inflow and outflow of atmospheric air at the top of the column. Gastight piston pumps (FMI lab pumps model QG) were used to control the air flow through the columns. Gas sampling ports (19) were placed with five cm interval from the bottom to the top (see Figure 5.1). To reach the natural bulk density of compost in the installed biowindow the compost was gently pressed together in the column. Five centimetres of the compost were placed inside at a time. Then it was pounded lightly with a metal stick that had a rubber end. To avoid ending up with layers, the top of each portion was gently loosened before the next amount of compost was added. The columns were filled to approximately 8 cm from the top of the column. The average bulk density obtained in the laboratory columns was similar to the average biowindow bulk density.

The following two mass balances were used to obtain carbon dioxide production rates (M_{CO2}) and the oxygen consumption rates (M_{O2}).

Oxygen mass balance:

$$M_{O_2} = M_{O_2,OUT} - M_{O_2,IN}$$
$$M_{O_2} = Q_{OUT} \cdot C_{O_2,OUT} - Q_{IN} \cdot C_{O_2,IN}$$

Carbon dioxide mass balance:

$$M_{CO_2} = M_{CO_2,OUT} - M_{CO_2,IN}$$
$$M_{CO_2} = Q_{OUT} \cdot C_{CO_2,OUT} - Q_{IN} \cdot C_{CO_2,IN}$$

Where, Q_{IN} and Q_{OUT} were the inlet and outlet flux. C_{OUT} was the gas concentration, which was measured in the sampling point number 19. Subsequently it was hypothesized that there was a complete mixing in the small chamber between the compost surface and the top PVC cap (Figure 2.2). C_{IN} (inlet concentration) was a room air sample. The column area was used to obtain the areal flux value either in mol $m^{-2}hour^{-1}$ or in g $m^{-2}day^{-1}$.

Gas samples were taken using a syringe and transferred to sampling vacuum container (Exetainer). Finally, the gas composition was analyzed using gas chromatography as earlier described in the section about batch experiments.

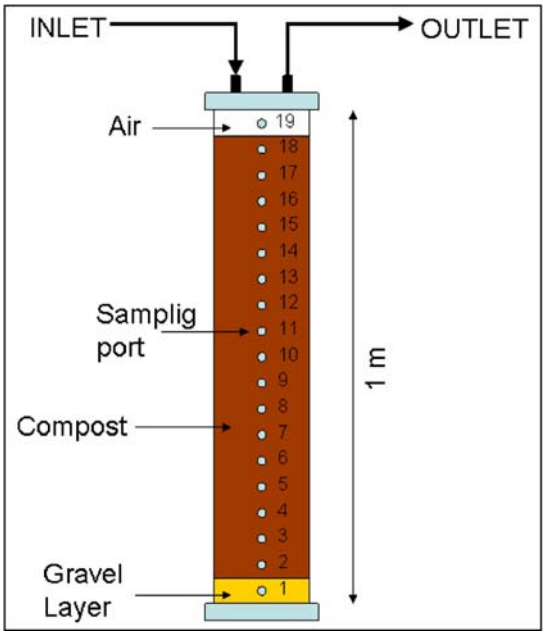


Figure 5.1 – Schematic picture of a column set up

Results

Batch experiments – respiration tests

Oxygen consumption due to respiration

Figure 5.2 shows the results from the respiration tests with the two compost materials compared to the control experiments. For all bottles there was a good agreement between duplicates. In figure 5.2 it can be seen that oxygen is used and carbon dioxide is being produced indicating respiration. The controls showed stable concentrations indicating no losses. The O_2 consumption and CO_2 production rates are shown in table 5.2. The compost sampled at the high emission area had slightly higher oxygen consumption (29.4 µg O_2/g DM/h) in comparison to the compost sampled at the medium emission area (25.8 µg O_2/g DM/h), which might be due to a higher organic content generated from the higher methanotrophic microbial activity at the high emission area (also see next section). Overall the compost material had an average oxygen consumption rate of 27.6 µg O_2/g DM/h. Surprisingly, this is significantly higher than the O_2 consumption measured initially during the pre-testing of the compost material, where the O_2 consumption rate was determined to 3.8 µg O_2/g DM/h (Pedersen et al. 2008b). A plausible explanation is that the compost sampled in the biowindow had a higher fraction of coarse material, which had partly been sorted out in the initial test as smaller test bottles (100 mL) were used and as this coarser fraction was difficult to get into the bottles. Previous experiments have shown that the coarser fraction of the compost holds a larger share of woody material and thus have a higher oxygen consumption rate (Pedersen et al., 2008). Furthermore, it is possible that the compost material from the biowindow have a higher organic content due to growth of bacteria and accumulation of biomass after almost 8 month of methane exposure in the field.

Overall the respiration test show that the compost placed in biowindow 1.1. has a relatively high oxygen consumption (27.6 µg O_2/g DM/h) comparable to the recommended threshold values of 48 µg O_2/g DM/h (over 7 days), which characterize a mature and stabilized compost.

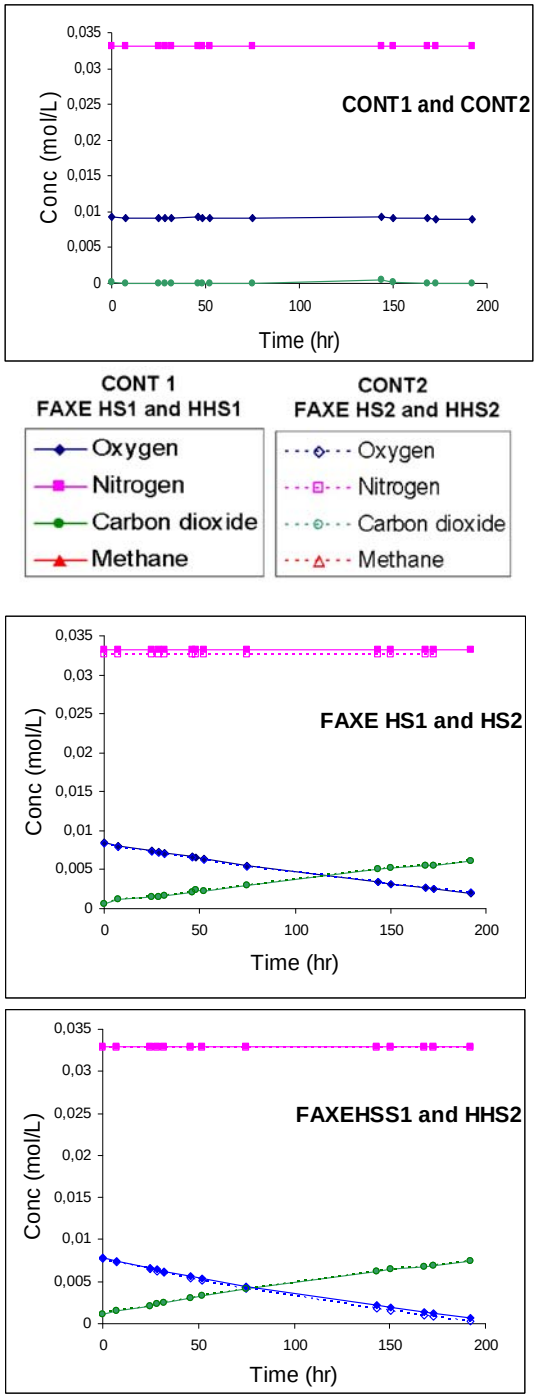


Figure 5.2. Respiration tests: gas concentration as function of time for two samples, HS and HHS and for control sample.

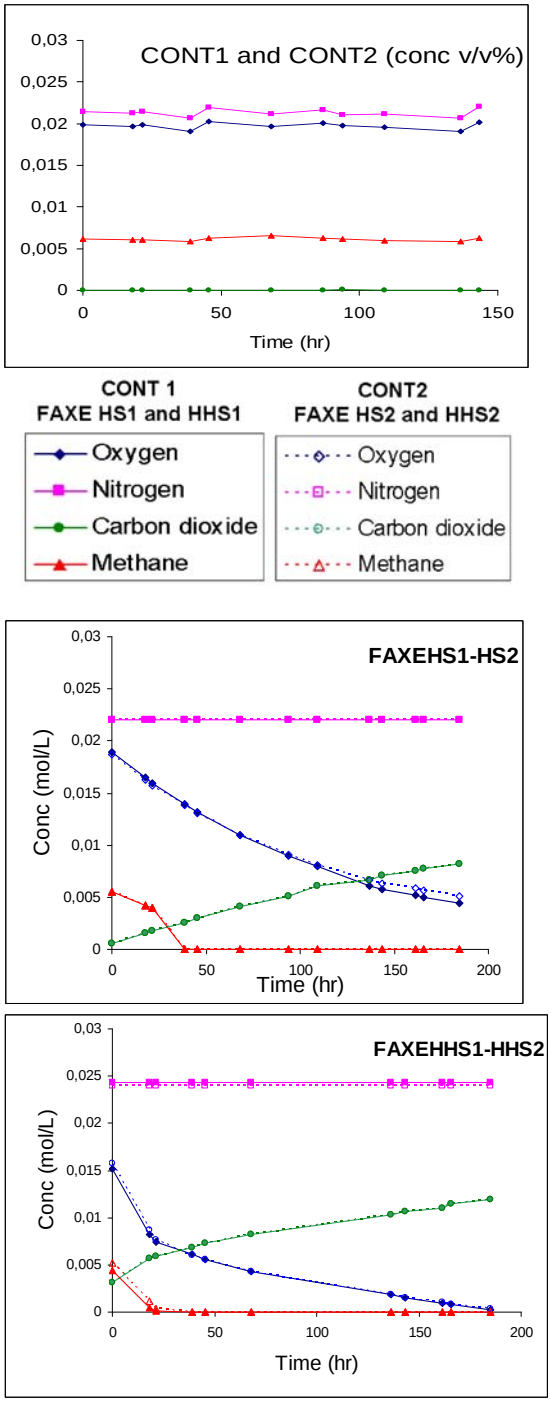


Figure 5.3. Methane oxidation tests: gas concentration as a function of time for two samples HS and HHS

Table 5.2. Carbon dioxide production, oxygen demand and standard deviation of the 2 different compost sample from the 2 sample points in the biowindow V1.1 (HS and HHS).

	Oxidation experiment			Respiration experiment	
Compost type	Methane oxidation μg gDM^{-1} $hour^{-1}$	Oxygen demand μg gDM^{-1} $hour^{-1}$	CO_2 production μg gDM^{-1} $hour^{-1}$	Oxygen demand μg gDM^{-1} $hour^{-1}$	CO_2 production μg gDM^{-1} $hour^{-1}$
Compost HS1	-14.7	-62.9	42.9	-26.3	30.3
Compost HS2	-14.7	-59.6	38.7	-25.4	29.2
Average	**-14.7±0.0**	**-61.3±2.3**	**40.8±3.0**	**-25.8±0.6**	**29.7±0.7**
Compost HHS1	-80.6	-262.0	136.8	-30.1	35.3
Compost HHS2	-79.1	-253.2	122.7	-28.7	32.6
Average	**-79.8±1.1**	**-257.6±6.2**	**129.8±10.0**	**-29.4±1.0**	**33.9±1.9**
Overall average				**-27.6±2.2**	**31,8±2.7**

Methane oxidation capacity

Figure 5.3 shows the results of the methane oxidation experiments. In all bottles methane and oxygen concentrations declined over time while carbon dioxide increased, suggesting that methane oxidation was taking place (Figure 5.3). Lag phases were never observed, indicating that the bacteria were well adapted to oxidizing methane. The methane oxidation rate was 14.7 μg CH_4/g dry DM/h and 79.8 μg CH_4/g dry DM/h for the compost sampled at the medium emission area and the high emission area, respectively. The almost five times higher oxidation rate seen for the compost sampled at the highest emission area in comparison to the compost sampled at the medium emission area makes sense as this first mentioned area most likely receive more methane and thus held more favorable conditions for methanotrophs. The obtained methane oxidation rates are comparable to the methane oxidation rates of 53 μg CH_4/g dry DM/h obtained in the initial test. Respiking, the bottles with methane lead to higher methane oxidation rates (up to 161 μg CH_4/g dry DM/h) indicating growth. The higher methane oxidation rate seen at the hotspot area is due to an increase in biomass after a longer period with methane exposure.

The respiration tests showed that a part of the oxygen consumption and carbon dioxide production in the compost microcosms is due to the activity of other compost respiring bacteria, which are oxidizing the organic material to carbon dioxide competing with the methane oxidizers for oxygen. The oxygen consumption of the compost material is expected to relatively independent of where the compost is sampled in the biowindow as also indicated by the respiration experiments. The oxygen consumption due to respiration accounted for approx. 11% and 42% of the total oxygen uptake during methane oxidation in the compost sampled in the high and medium emission area, respectively. Similar experiments conducted with landfill gas exposed soils have shown that the oxygen consumption due to respiration only made of 8% of the oxygen consumption in methane oxidation experiments, showing that methane oxidizers dominated the oxygen consumption (Scheutz and Kjeldsen, 2004). In comparison, the compost experiments indicate that a significant part of the oxygen diffusing into the compost biowindow will be used for respiration of the organic part of the compost.

Based on the measured carbon dioxide evolution in respiration tests incubated with atmospheric air, incorporation of carbon into biomass was approximately 75% and 56%, calculated as $C_{assimilated} = C_{substrate,CH4} - C_{mineralized,CO2}$ and subtracting the background soil respiration. In comparison, Kightley et al. (1995) found that 69% of oxidized methane was assimilated into biomass in soil cores. Similar findings were obtained by Börjesson et al. (1998) who found CO_2/CH_4-ratios between 0.17 and 0.36 indicating that between 64% and 83% was assimilated.

Column experiments: gas concentration profiles and gas emission from the respiration process

Figure 5.4 shows the gas concentration profiles of oxygen, carbon dioxide and nitrogen in the column experiments simulating respiration by atmospheric oxygen up-take. The charts were obtained plotting gas concentration (%v/v) versus column depth (cm) each point representing the gas concentration measured in sample taken from different sampling ports along the whole column. In the control column containing sterilized sand, the gas concentrations were constant with depth and resembled the composition of atmospheric air. Results showed a good agreement between the two profiles of column 1 and 2 containing compost. The nitrogen profiles of the columns filled with compost show that atmospheric air is penetrating throughout the whole column. The oxygen profile taken at day 3 showed a decrease from the top of the column and down to 40 cm. This together with the increasing carbon dioxide concentration with depth indicates respiration. Oxygen was detected deeper in the column on day 3 than on day 16. It occurred because the respiration process was higher on day 16 than on day 3 and oxygen was consumed faster than it is diffusing into the column.

Figure 5.4 also shows the gas concentration profile measured in the field at V1.1H in window 1.1. There is a good agreement between the field gas profiles and the column experiments profiles indicating that the column experiments simulate the processes in the compost cover environment very well. At monitoring point V1.1H in biowindow 1.1., the carbon dioxide emission is believed to mainly be due to compost respiration as no methane was ever detected in the deeper parts of the biocover window. The gas profiles from the columns as well as those in the field showed elevated carbon dioxide concentrations throughout the compost layer and below 40 cm carbon dioxide concentrations were above 20 %.

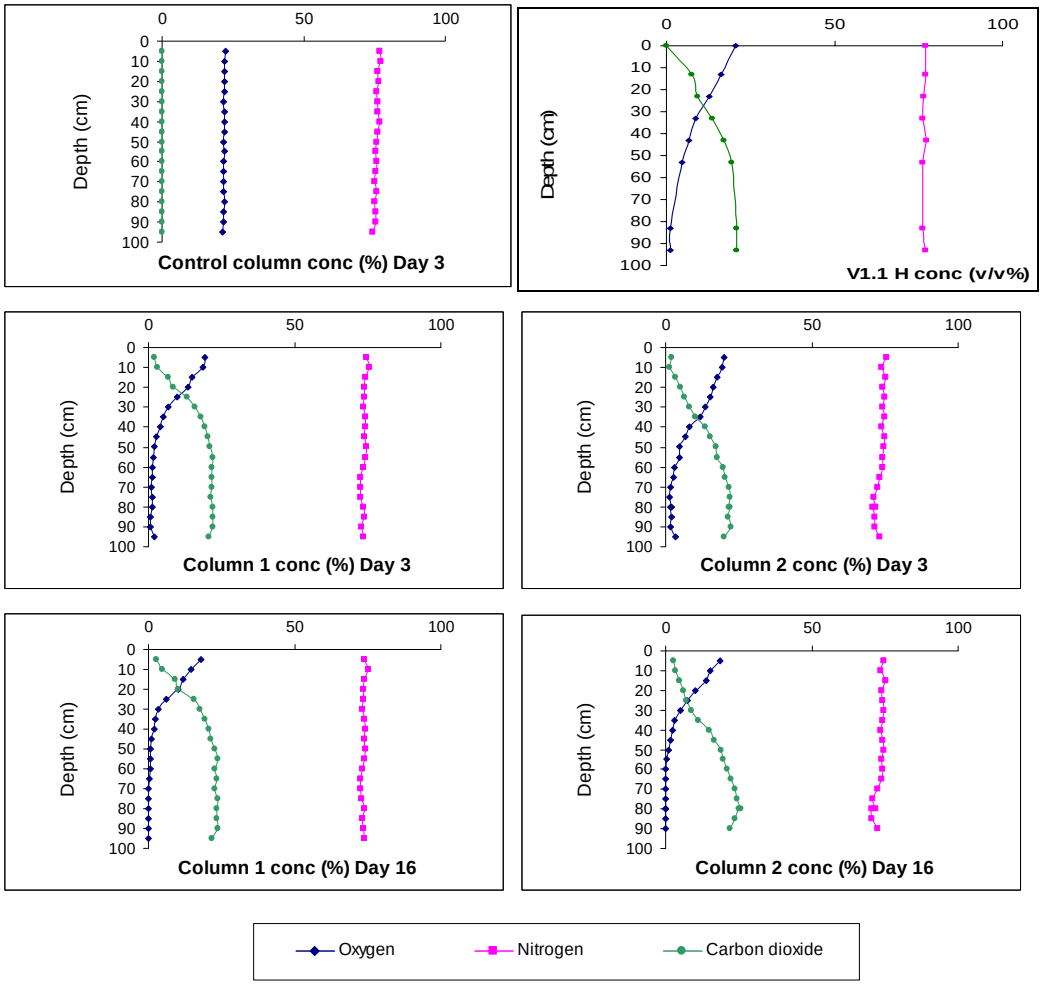


Figure 5.4. Gas profiles: control column of day 3 (first row), field deep probe profile (V1.1H see figure 3.8), column 1 (left) and column 2 (right) of day 3 (second row) and day 16 (third row).

Carbon dioxide production and oxygen consumption rates over time are given in Figure 5.5 and Table 5.3. Figure 5.4 shows that the oxygen consumption and the carbon dioxide production (g m^{-2} day^{-1}) increased over time, indicating that the compost respiration increased over time, accordingly. The average carbon dioxide production and oxygen consumption rates for the test period were 107±14 g m^{-2} day^{-1} and 63±12 g m^{-2} day^{-1} respectively.

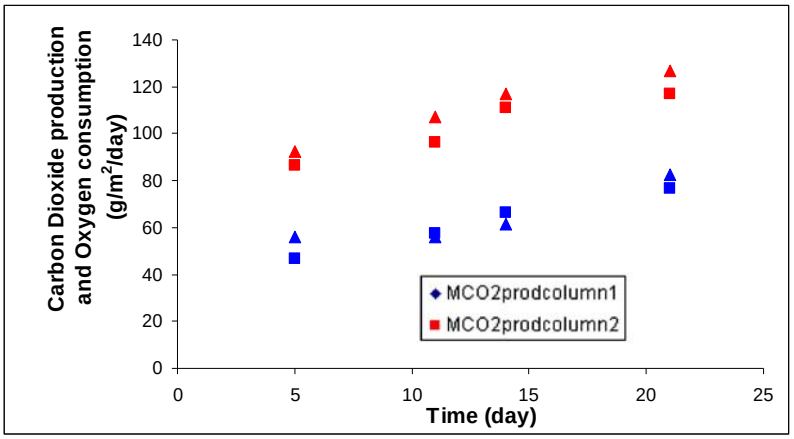


Figure 5.5. Carbon dioxide production (red) and oxygen consumption (blue) from day 3 to day 16, column 1 is indicated with triangle, column 2 with a rectangle

Table 5.3. Carbon dioxide (g m^{-2} day^{-1}) emission rate from the column at different time

	Time	**CO_2 production**	**O_2 consumption**
	day	g m^{-2} day^{-1}	g m^{-2} day^{-1}
Column 1	5	92	56
Column 1	11	107	47
Column 1	14	117	56
Column 1	21	126	57
Average		111±13	54±4
Column 2	5	87	61
Column 2	11	96	66
Column 2	14	111	82
Column 2	21	116	77
Average		103±12	72±8
Total		107±14	63±12

Table 5.4 shows a comparison between carbon dioxide production and oxygen consumption rates obtained in batch and column experiments. By assuming that in the upper 1/3 of a 1m thick compost layer oxygen concentrations are sufficiently high to support respiration, carbon dioxide production and oxygen consumption rates were calculated (in g m^{-2} day^{-1}) based on the rates obtained in the batch experiments and compared to the column results. The average value of carbon dioxide production (127.5 g m^{-2} day^{-1}) and oxygen consumption (111 g m^{-2} day^{-1}), compares relatively well with the column results. The higher oxygen production rate based on the batch experiments is probably due to a more efficient oxygen transport in the batch experiments in comparison to the columns where oxygen transport is limited by diffusion from the surface of the compost layer.

Table 5.4. Water content, temperature and carbon dioxide emission rates in (g m^{-2} day^{-1}) for column and batch experiments.

Experiment	**Water content**	**Tempe-rature**	**Bulk density**	**Carbon Dioxide production**		**Oxygen consumption**	
	g/100g DM	ºC	kg/m^3	µg gDM $^{-1}$ $hour^{-1}$	g m^{-2} day^{-1}	µg gDM $^{-1}$ $hour^{-1}$	g m^{-2} day^{-1}
Column 1	71.1	22	571.3	28[a]	126[c]	13[a]	57[c]
Column 2	71.1	22	605.3	26[a]	116[c]	17[a]	77[c]
Average				27	121	15	67
Batch-high emission (HHS)	72.2	22	684.0	33.9±1.9[b]	136[d]	25.8±0.6[b]	117[d]
Batch-low emission (HS)	72.2	22	684.0	29.7±0.7[b]	119[d]	29.4±1.0[b]	105[d]
Average				31.8	127.5	27.5	111

[a] Carbon dioxide production and oxygen production in the column experiments in µg gDM^{-1} $hour^{-1}$.
[b] Respiration tests results.
[c] Carbon dioxide production and oxygen production fluxes in the column experiments in the last day of measurements.
[4] Carbon dioxide production and oxygen production assuming that 1/3 of the compost layer produces carbon dioxide from respiration.

Overall the respiration test showed that the compost placed in biowindow 1.1. has a relatively high oxygen consumption (27.6 µg O_2/g DM/h) comparable to the recommended threshold values of 48 µg O_2/g DM/h (over 7 days), which characterize a mature and stabilized compost.

The methane oxidation rate was 14.7 µg CH_4/g dry DM/h and 79.8 µg CH_4/g dry DM/h for the compost sampled at the medium emission area and the high emission area at biowindow 1.1, respectively. The oxygen consumption due to respiration accounted for approx. 11% and 42% of the of the total oxygen uptake during methane oxidation in the compost sampled in the high and medium emission area, respectively. Column studies simulating compost respiration in a biocover window showed average carbon dioxide production and oxygen consumption rates of 107±14 g m^{-2} $day^{-1}$and 63±12 g m^{-2} day^{-1}, respectively. Gas profiles from the columns showed elevated carbon dioxide concentrations throughout the compost layer and below 40 cm carbon dioxide concentrations were above 20 %.

Overall the results showed that respiration of compost material might generate significant carbon dioxide emissions. In landfill compost covers, methane oxidation will compete for oxygen limiting respiration and thus the contribution of carbon dioxide production produced from respiration is expected to be lower than the production rate of 107 g m^{-2} day^{-1} observed in compost columns not receiving methane. The carbon dioxide emissions from landfill compost covers consists of carbon dioxide produced from methane oxidation and respiration as well as carbon dioxide generated within the waste. In reality it is very difficult to distinguish the different contributions to the overall carbon dioxide emission.

Based on the conducted experiment it can be concluded, that in compost covers where the methane load is small, high carbon dioxide emissions might be due to respiration of the compost material especially if the compost is not mature and stable.

6 Gas transport and oxidation in established biocover windows

Additional activities were initiated on established biocover windows to elucidate the reasons to the hot spots on the biowindows observed earlier. The additional detailed studies were carried out on two of the biowindows, V1.1 and V7. Surface fluxes of methane and carbon dioxide was measured by mobile flux chambers. Also gas profiles of the four main components (methane, carbon dioxide, oxygen and nitrogen) were obtained. On window 7, the compost was removed after completion of one measurement campaign, to evaluate load to the location from the gas distribution layer. On window 1.1 a high number of flux measurements were performed to study spatial variation in surface fluxes in more detail.

6.1 Window 1.1

Objective

A detailed study is done on window 1.1 to determine the total emission from the biowindow, and to evaluate how the spatial difference in load to the biocover window affects methane oxidation.

6.1.2 Study Window

The biowindow 1.1 is placed on the finally covered part of unit 1.1. It has an area of 10x10m and is sloping downwards towards the rim of the landfill (10-15%) towards the south east and a big hotspot is present in the upper part of the biocover window (towards the middle of the landfill, the western part of the window). February 2008 2-3 meters of clay was found under the study window and a 1.5m wide trench was dug and filled with tree roots to allow contact between landfill body and biocover window. The load to the window until digging the trench is believed to come from other locations in the landfill through the root blockage layer.

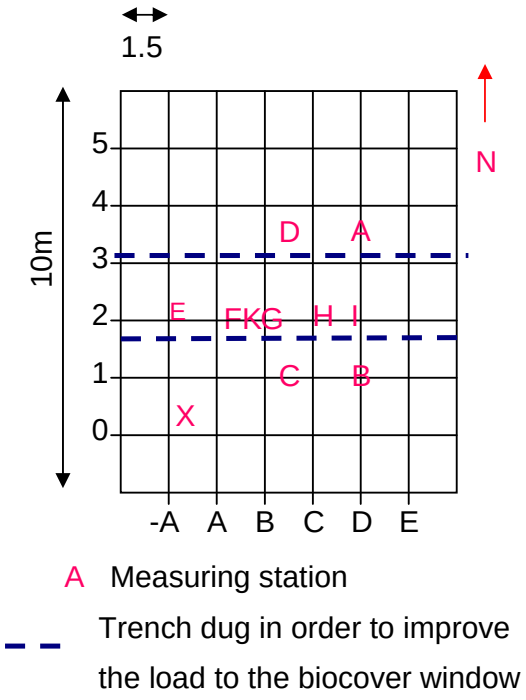


Figure 6.1: A simple outline of the biowindow 1.1. A transect east west of the biowindow is seen together with the original measuring points; A, B, C and D. Furthermore the trench is marked and a surface emission grid is shown.

Method

In order to determine the development of total emission and methane oxidation on the window, a series of surface emission measurements was made over the spring 2008 on selected grid points shown in figure 6.1. Based on the flux emission measurements surfer elaborations has been prepared to determine total emissions of the hotspot.

To evaluate how landfill gas load is spatially distributed over the window a measuring transect is made in west to east direction on the biocover window. From FID measurements it is known that the highest emissions are seen along the southern and western edge and the corner where an additional measuring station has been placed.

Providing the overall methane mass balance with a thorough and precise estimate of total methane emission a surface emission measurement on all grid points seen in figure 1 was performed on December 1st 2008.

Results

In table 2.1 results from the 7 emission measurement campaigns conducted on window 1.1 in the spring 2008 is listed together with the temperature of the measuring day and the pressure change 24h prior to the beginning of the measuring day (8am to 8am). The pressure change over the measuring day (8am to 4pm), the total and average emission of carbon dioxide and methane and the estimated methane oxidized is also seen. The average percent oxidation was 29% over the 7 campaigns, with the highest percent oxidation on 60% on the 25th of June 2008. On this day a rate of 110 g m^{-2} day^{-1} was achieved, which is 81 % of the initial goal. It was estimated that a total

of 5.4 kg d^{-1} was oxidized in biowindow 1.1 this day, which corresponds to app. 0.7 % of the total methane emission determined at the baseline study.

Table 6.1 Results from 7 campaigns on window 1.1. Average oxidation rates are based on 13, 9, 11, 17, X, 14 and 24 flux measurements for the 7 respective campaigns and a Surfer elaboration on the 49 m^2 big hotspot on the SW part of window 1.1.

Date	**Temp**	**ΔP[a]**	**ΔP[b]**	**CO_2 flux**	**CH_4 flux**	**CO_2 flux**	**CH_4 flux**	**Methane Oxidised[c]**			
	C°	hPa h^{-1}	hPa h^{-1}	kg day^{-1}		g m^{-2} day-1		mole m^{-2} d^{-1}	%	g m^{-2} day^{-1}	kg day^{-1}
15-04-2008	8.6	0.23	0.2	13.1	3.6	267	73	1.39	23.3	22.2	1.1
23-04-2008	9.5	0.23	0.15	10.1	2.9	205	58	0.86	19.2	13.8	0.7
24-04-2008	10.8	0.11	-0.12	13.6	5.2	276	105	0.63	8.7	10.0	0.5
08-05-2008	19.3	-0.15	-0.08	21.7	5.0	442	102	2.36	27.0	37.8	1.9
04-06-2008	18.2	0.16	0.13	19.5	4.8	398	96	2.01	25.1	32.2	1.6
25-06-2008	15.8	-0.01	-0.50	34.4	3.7	701	74	6.94	60.0	111.0	5.4
30-06-2008	17.3	-0.02	0.43	34.6	6.5	705	133	5.43	39.5	86.8	4.3
Average	**12.8**		**-0.1**	**21.0**	**4.5**	**427.7**	**91.6**	**2.8**	**29.0**	**44.8**	**2.2**
01-12-2008	4.2	0.4	-0.38	49.0	29.8	613	373	-1.03	-1.6	-27.0	-2.2

[a]Pressure change 24h prior to the beginning of the measuring day (8am to 8am) [b]Pressure change over the measuring day (8am to 4pm)[c] The methane oxidized is calculated as presented in Chapter 2 and subtracted temperature dependent respiration determined in Chapter 5: Compost respiration.

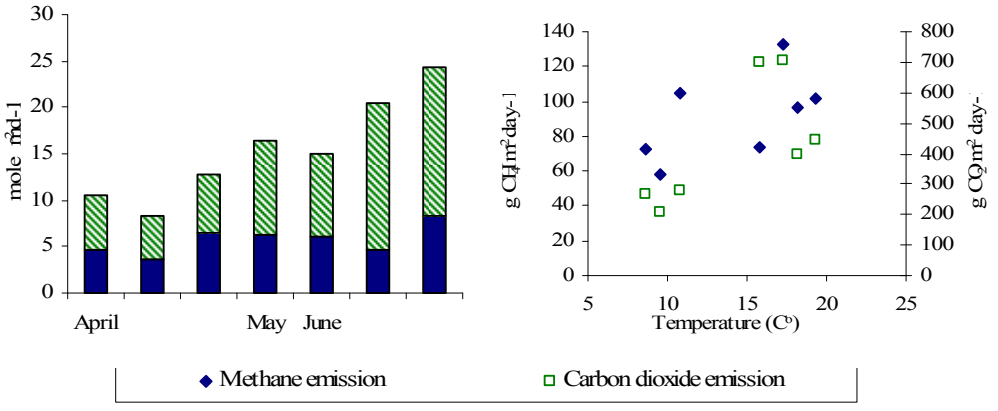


Figure 6.2. Graphical presentation of the emission data in table 6.1. Left figure: Hatched part of the columns is the carbon dioxide emission and the filled out part is the methane emission. Right figure: Temperature dependency is seen for both methane emission and carbon dioxide emission.

In figure 6.2 a graphical presentation of the emission data in table 6.1 can be seen. Emission of both methane and carbon dioxide was increasing over time as the temperature rises. This is most likely due to less water logging of the system and better load. There is no relation to the barometric pressure change so other parameters most determine the gas load to the biocover window. Carbon dioxide emissions were

increasing steeper than methane and percent methane oxidation is also increasing, which most likely is due to the higher temperature resulting in higher methane oxidation rates over time. Though the hotspot area of the window was also getting bigger over time making a bigger part of the biocover window active, which could increase the methane oxidation percent. Furthermore, it seemed like the digging of the trench did have some effect especially in the western part of the biocover window. In figure 4.3 carbon dioxide emissions before and after the improvements can be seen and there was a very obvious change. The after improvement emission pattern was higher above the trench (results at 3 m in the grid). So a more thorough investigation of emissions shows that the improvements of the system most likely did increase the load of landfill gas to the biocover window 1.1.

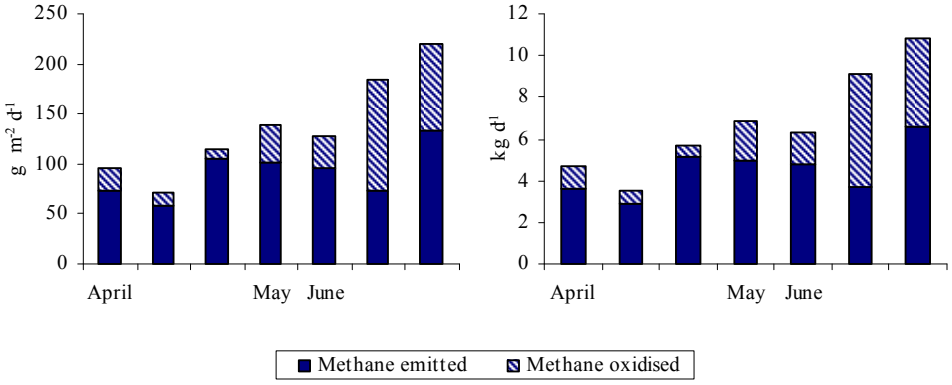


Figure 6.3. Graphical presentation of the average (g m^{-2} d^{-1}) methane emitted and oxidized and the total (kg d^{-1}) methane emitted and oxidized from table 6.1.

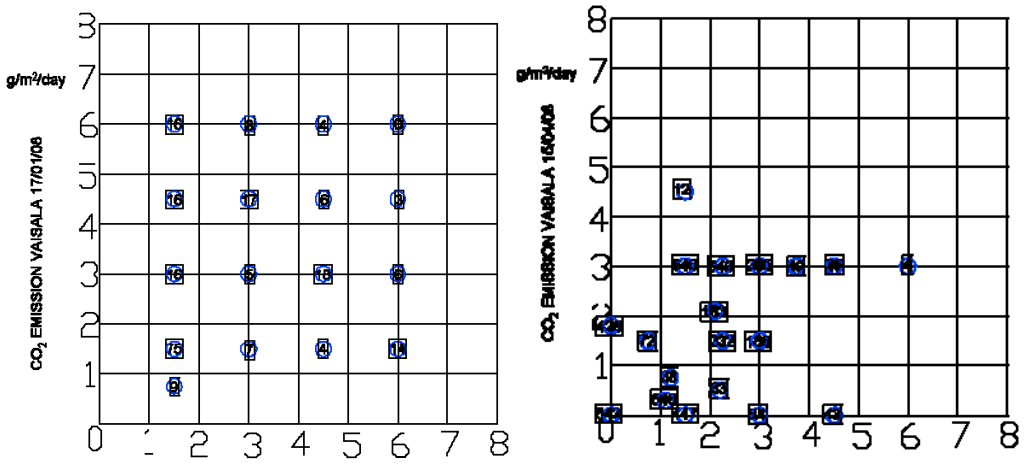


Figure 6.4. Emission pattern in window 1.1 before and after the improvement of the biocover system. The grid pattern is in meters.

In figure 6.5 the gas concentration profiles over the transect E, F, G, H and I can be seen.

Methane was present in the profile for the measuring point E, F and G and the mol ratio (CH_4/CO_2) is getting lower and lower with the distance from the edge of the biowindow. The profiles H and I look like the profiles presented earlier though oxygen penetrates deeper into the I profile than the H profile and carbon dioxide concentrations are higher for the H profile.

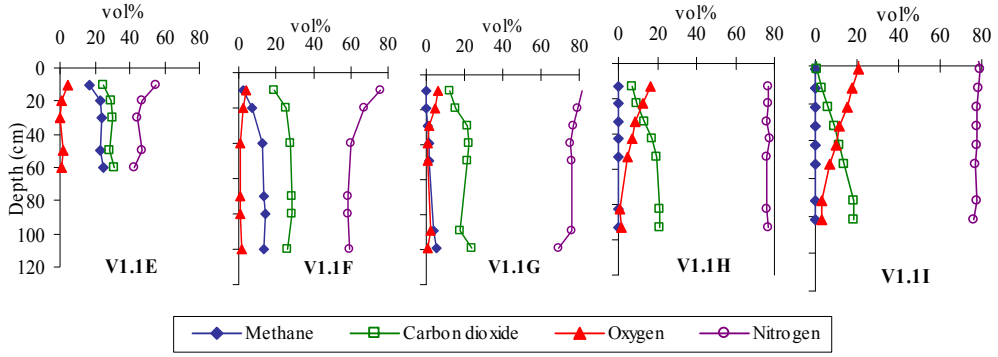


Figure 6.5. Gas concentration profiles over the transect E, F, G,H and I as seen in figure 6.1

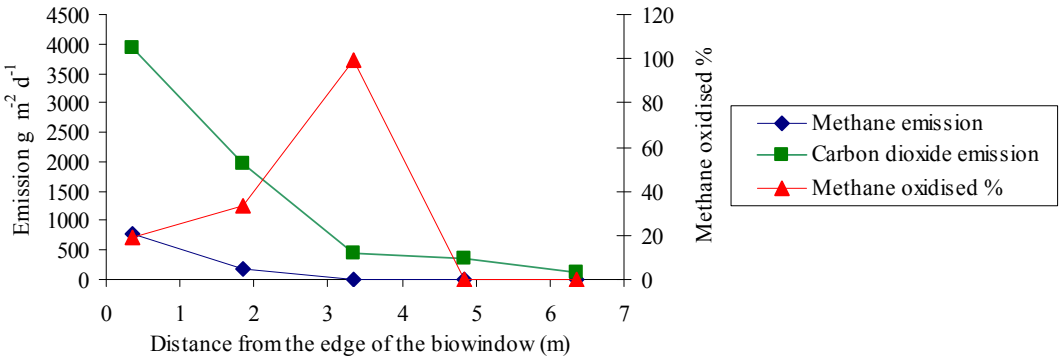


Figure 6.6. The emission of methane and carbon dioxide and percent methane oxidation along the transect.

In figure 6.6 the emission of methane and carbon dioxide and percent methane oxidation along the transect is shown. Close to the edge, the emissions were very high and the retention time was too low for methane oxidation to occur. Three to four meters from the edge, optimum conditions were present for the methane oxidation to occur and 80-100% oxidation was seen.

In figure 6.7 is presented the surface flux emission measurements done on Dec 1st 2008 under decreasing pressure (ΔP=-0.38 hPa h^{-1}). It can be seen how the hotspot was covering almost the entire filter and elevated emissions (>1000 g $m^{-2}d^{-1}$) were also seen on the northern edge of biowindow. This was not the case in the spring emission measurements (e.g. June 25th, ΔP=-0.5 hPa h^{-1}) and the stable increase in the emission pattern is most likely due to the final covering of a bigger part of the landfill. Unit 4 and 5 was finally covered September 2008 and this probably reduced the alternative escape routes for the landfill gas. This emphasizes the importance of installing biocovers and doing investigation of biocover performance on closed finally

covered landfills, though it is also an advantage to be able to build the biocover windows into the finally covering as it will reduce costs significantly.

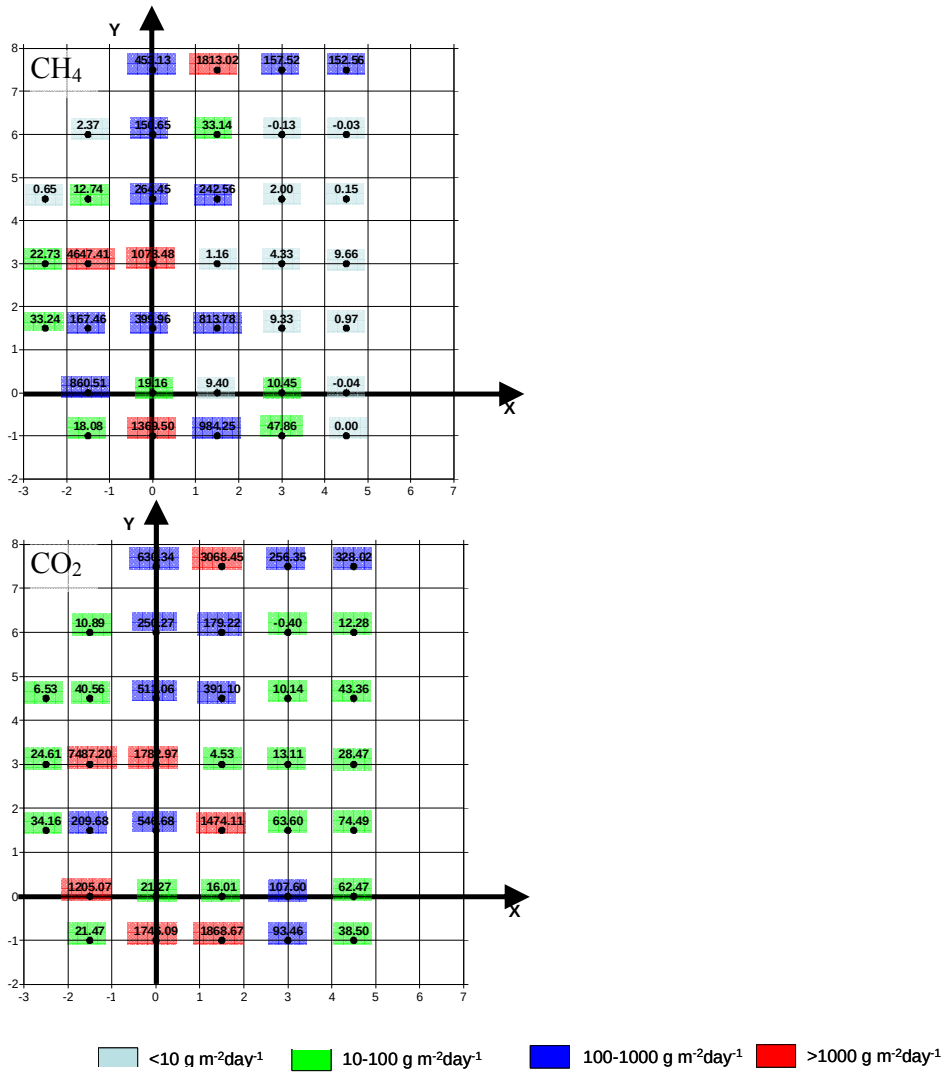


Figure 6.7. Surface flux emission measurements done on Dec 1st 2008 under decreasing pressure (ΔP=-0.38 hPa h^{-1})

Furthermore a FID screening around the window showed elevated conc. on an area of app. 20 times 20m south west of the biowindow.

6.2 Window 7

Introduction and objective

Initial field measurements of methane (CH_4) and carbon dioxide (CO_2) emissions from the installed biowindows at Fakse had shown high carbon dioxide emissions and

low CH_4 emissions indicating significant CH_4 oxidation in the compost material placed in the biowindow. However, gas concentration profiles measured in the compost window showed elevated carbon dioxide concentrations throughout the compost cover, but no CH_4 not even in the deepest gas probes (100 cm below surface). Based on these observations two hypothesis were possible: either all the CH_4 going to the bio-window was oxidized in the gas distribution layer beneath the compost layer, or the CH_4 load to the biowindow was insignificant and the measured carbon dioxide emissions solely a result of respiration of the compost material itself.

The objective of this task was to quantify the CH_4 oxidation in biowindow 7 by comparing measurements of the CH_4 emitted from the biowindow with the CH_4 load to the biowindow. The last mentioned was determined by excavating the compost placed in the biowindow followed up by flux chamber measurements on the surface of the gas distribution layer. Furthermore, analysis of stable carbon isotopes in CH_4 emitted from both the compost surface and from the gas distribution layer was conducted to quantify CH_4 oxidation.

Methodology

Field campaigns and weather situation

In order to meet the objective three field campaigns were conducted during October and December 2008. The first field campaign included surface CH_4 screenings, flux chamber measurements, installation of gas probes and isotopic analysis of gas samples taken from both flux chambers and gas probes. After the first field campaign, the compost in the biowindow was excavated and surface CH_4 screenings and flux measurements were repeated. Table 6.2 reports the weather situation in terms of changes in barometric pressure during the three field campaigns. All campaigns aimed at conducting the measurement during stable atmospheric conditions as it is well known, that changes in the barometric pressure can impact the gas emission from landfills. However, during the second field campaign a small decrease in barometric pressure was observed why it was decided to conduct another measuring campaign to obtain data comparable to the first campaign.

Table 6.2. Overview of the three field campaigns and weather situation in terms of changes in barometric pressure during the three field campaigns.

Field campaign	**Date**	**Temperature**	**Change in barometric pressure during campaign**	**Change in barometric pressure 24 hours before and after campaign**
		ºC	hPa	hPa
1	Oct 29, 2008	6.2	-1.1	-4.7
2	Dec 1, 2008	3.6	3.1	-5.8
3	Dec 3, 2008	1.0	4.2	4.2

Surface screening and flux chamber measurements

In order to investigate the CH_4 surface emission from window 7, surface screenings of CH_4 concentrations in ambient air were carried out. The screenings were done by walking over the surface of the biocover window recording the ambient CH_4

concentrations close to the surface using a Photovac MicroFID analyzer. When CH_4 concentrations above background were measured (> 2 ppmv), the "hotspot" area was flagged and the surface area measured. The surface screening gives a qualitative impression of whether and where gas is emitted from the window.

In order to quantify the emission from window 7, flux chamber measurements were conducted at the hotspot areas indentified during the surface screening. The total CH_4 and carbon dioxide emission from window 7 was calculated based on the measured emissions and the area of the individual hotspots. Depending on the size of the hotspot area several flux chamber measurements (3 to 6) were made at each individual hotspot. The procedure for flux chamber measurements is described in section 2. During each field campaign between 25 and 31 flux chamber measurements were done covering both hotspot areas with high ambient CH_4 concentrations and areas with background CH_4 concentrations. At each campaign 6 to 8 chambers were sampled for isotopic analysis in order to quantify CH_4 oxidation.

Installation of gas profiles

Gas profiles were determined by installing gas probes and taking samples at different depths in the compost cover. The gas probes consisted of steel tubes (16 mm ID), which were closed in at the bottom and provided with slits over the lower 5 cm. The steel probes were hammered into the ground at different depths. In general samples of the main components (CH_4, CO_2, O_2, and N_2) were taken at 10, 20, 30, 40, 60, 80, 100 and 180-cm depth. Gas samples (5 mL) were withdrawn with a syringe through a closed sampling system and stored in vacuumed glass bottles. The gas probes were flushed before sampling by pumping approximately two times the dead volume of the probes. Thirteen compost profiles were collected from the window including hotspot areas and background areas. The gas probes were inserted close to the flux chambers. Five gas probes were sampled for isotopic analysis in order to quantify CH_4 oxidation.

Results

First field campaign – before excavation

Table 6.3 shows the ambient CH_4 concentrations measured on window 7. The surface screening showed ambient CH_4 concentrations ranging from background concentrations around 2 ppmv up to 3000 ppmv indicating high spatial variation with "hot spots" areas showing high CH_4 concentrations. In total 4 areas were identified based on the measured elevated CH_4 concentrations, clearly indicating that CH_4 is emitted from a limited number of smaller areas on the surface of window 7. The 4 areas varied in size from 13.5 to 57.3 m^2.

Emissions of CH_4 varied between –0.11 and 273 $g \cdot m^{-2} \cdot d^{-1}$; with the highest fluxes measured in the hotspot areas identified during the screening. Emissions measured randomly outside the hotspot areas generally exhibited negative CH_4 fluxes (-0.02 to -0.08 $g \cdot m^{-2} \cdot d^{-1}$) indicating oxidation of atmospheric CH_4 and no landfill CH_4 emissions. Negative CH_4 fluxes have previously been reported in other field studies (Bogner et al., 1997, Scheutz et al., 2003, Scheutz et al., 2008). Emissions of CO_2 varied between 7.35 to 2026 $g \cdot m^{-2} \cdot d^{-1}$, and as for CH_4 the highest fluxes were associated with hotspots also showing high CH_4 fluxes. Figure 6.8 shows the CH_4

emissions (g m^2 d^{-1}) measured at window 7 at Fakse landfill. The four areas exhibiting high emissions were all close to the western edge of the biowindow.

Table 6.4 list the average CH_4 and CO_2 flux from the four hotspots and the remaining area of the biowindow, where random flux measurements were made. The average CH_4 emission for the four hotspots varied between 5.92 to 105.72 g m^{-2} d^{-1} whereas the average CH_4 emission for the remaining part of the window was -0.01 g m^{-2} d^{-1}. The total CH_4 emitted from the window was 11.6 kg d^{-1} with the majority (5.1 and 6.1 kg d^{-1}) of the emission coming from two hotspots located close to the edge of the biowindow (see figure 6.8). The average CO_2 emission for the four hotspots varied between 83.97 to 995.83 g m^{-2} d^{-1} whereas the average CO_2 emission for the remaining part of the window was 37.23 g m^{-2} d^{-1}. The total CO_2 emitted from the window was 143.43 kg d^{-1}. The relatively high CO_2 emissions in comparison to CH_4 indicate that a significant part of the generated CH_4 is oxidized to CO_2 before emitted to the atmosphere. However, it is also possible that a part of the emitted CO_2 is produced by respiration of the compost material placed in the biowindow. Column studies simulating compost respiration had shown CO_2 emission rates of 107 g m^{-2} d^{-1} (se chapter 5). The fraction of CH_4 oxidized can be determined by analysis of the stable carbon isotopes in CH_4. In situ determination of CH_4 oxidation is based upon measuring the difference in $\delta^{13}C$ between anoxic zone CH_4 and CH_4 emitted from the landfill cover soil which has been subjected to oxidation. Combined with measurement of the preference of the bacteria for $^{12}CH_4$ relative to $^{13}CH_4$, a quantitative estimate of the fraction of CH_4 oxidized as it passes through the landfill compost cover can be determined (Chanton et la., 1999; Liptay et al., 1998). Gas samples for isotopic analysis were taken from flux chambers in parallel with the CH_4 emission measurements. In total samples were taken from 8 chambers. The samples are currently being analyzed and we are awaiting the results.

Table 6.3 Ambient CH_4 concentrations and CH_4 and carbon dioxide emissions measured at hotspot areas on window 7 during the October 2008 field campaign. Table also shows the four areas in which the different hotspots were found.

Location	**Ambient CH_4 conc.**	**Methane emission**	**Carbon dioxide emission**	**Methane fraction of total emission**	**Carbon dioxide fraction of total emission**	**Area**
	ppmv	g m^{-2} d^{-1}	g m^{-2} d^{-1}	%	%	
HS1	43	0.19	23.60	2	98	Area 1
HS2	175	6.94	35.96	35	65	Area 1
HS3	11	9.08	30.32	45	55	Area 1
HS4	17	0.14	7.35	5	95	Area 1
V7A	22	49.63	388.30	26	74	Area 1
HS6	29	0.70	18.28	9	91	Area 1
HS7	2	0.01	65.05	0	100	Random
HS8	19	56.42	715.30	18	82	Area 2
HS9	686	267.13	1876.73	28	72	Area 2
HS10	219	202.77	2026.51	22	78	Area 2
HS11	1048	2.35	329.93	2	98	Area 2
HS12	59	-0.07	30.66	0	100	Area 2
HS13	2	-0.02	66.45	0	100	Random
V7B	43	-0.04	38.75	0	100	Random
HS14	3	0.01	50.83	0	100	Random
HS15	700	273.35	919.51	45	55	Area 3
HS16	296	4.32	392.10	3	97	Area 3
HS17	127	21.49	422.78	12	88	Area 3
V7C	25	-0.08	104.64	0	100	Random
HS18	127	19.40	240.82	18	82	Area 4
HS19	26	4.41	326.41	4	96	Area 4
HS20	4	-0.11	148.38	0	100	Area 4
HS21	5	-0.01	60.04	0	100	Area 4
V7D	23	-0.02	15.58	0	100	Random
HS22	182	-0.03	23.54	0	100	Random
HS23	2	-0.02	11.28	0	100	Not on biowindow
HS24	2	0.02	51.31	0	100	Random
HS25	2	0.00	33.49	0	100	Random
HS26	2	-0.02	37.92	0	100	Random
HS27	2	0.02	108.94	0	100	Random
HS28	2	-0.03	15.77	0	100	Random

Table 6.4. Average methane and carbon dioxide emissions from hotspot areas on window 7 during the October 2008 field campaign. Table also shows the emissions from the remaining area of the biowindow excluding the hotspots where surface flux measurements were made randomly.

Location	No. of flux measure-ments in area	Area of hotspot m^{-2}	Average methane emission $g\ m^{-2}\ d^{-1}$	Total methane emission $kg\ d^{-1}$	Average carbon dioxide emission $g\ m^{-2}\ d^{-1}$	Total carbon dioxide emission $kg\ d^{-1}$
V7-1	6	39,3	11,11	0,44	83,97	3,30
V7-2	5	57,3	105,72	6,06	995,83	57,06
V7-3	3	51	99,72	5,09	578,13	29,48
V7-4	4	13,5	5,92	0,08	193,91	2,62
V7-5	12	1368,9	-0,01	-0,01	37,23	50,96
Total				**11,65**		**143,43**

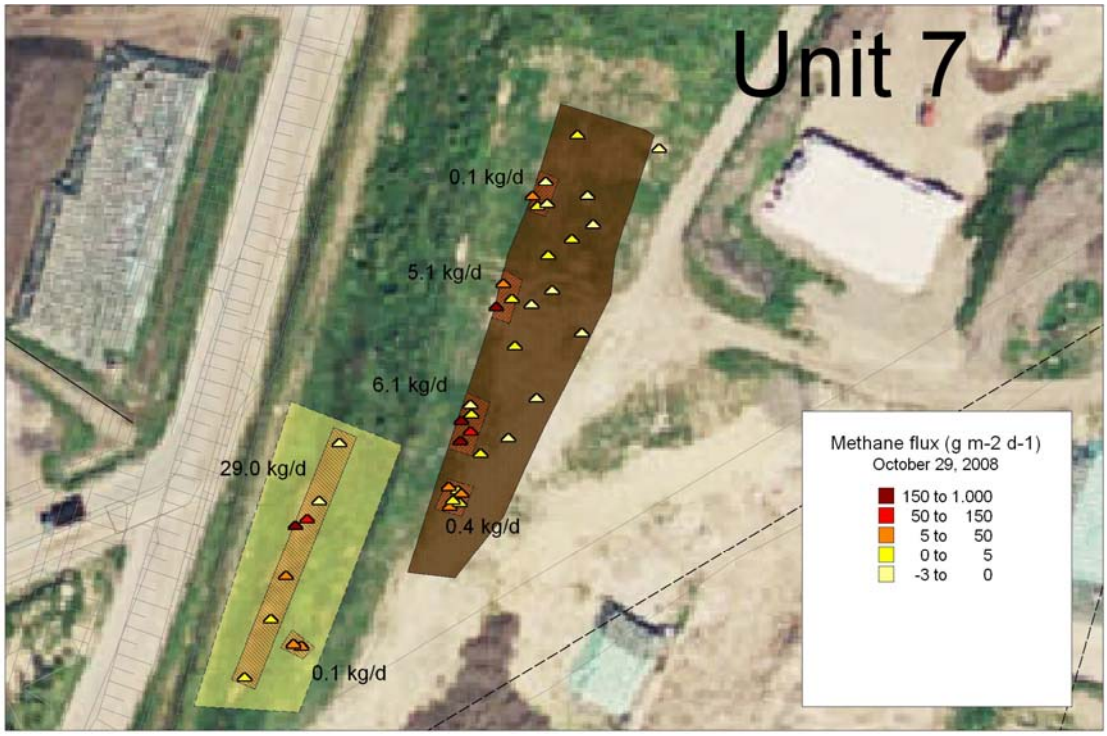


Figure 6.8. Methane emissions ($g\ m^2\ d^{-1}$) measured at biowindow 7 at Fakse landfill. Four areas exhibiting high emissions were identified and the total methane emitted ($kg\ d^{-1}$) from the individual areas determined.

Second field campaign – after excavation of the compost material

After the first field campaign the compost layer was removed and surface screening and flux measurements repeated on top of the gas distribution layer consisting of gravel. Table 6.5 shows the ambient methane concentrations measured on window 7 after having removed the compost layer. The surface screening showed ambient methane concentrations ranging from background concentrations around 2 ppmv up to 98 ppmv. Based on the surface screening five areas with elevated methane concentrations were identified. The five areas varied in size from 1.8 to 12.48 m^2.

Emissions of CH_4 varied between –1.04 and 93.51 g m^2 d^{-1}; whereas emissions of CO_2 varied between 0.12 to 2000 g m^2 d^{-1}. The highest fluxes were measured in the hotspot areas identified during the screening. Emissions measured randomly outside the hotspot areas generally exhibited negative CH_4 fluxes (-0.01 to -0.06 g m^2 d^{-1}). Figure 6.9 shows the methane emissions (g m^2 d^{-1}) measured at window 7. Four of the areas exhibiting high emissions were close to the western edge of the biowindow whereas one area was close to the eastern edge of the biocover window.

Table 6.6 list the average CH_4 and CO_2 flux from the five hotspots and the remaining area of the biowindow, where random flux measurements were made. The average CH_4 emission for the four hotspots varied between 5.08 to 47.89 g m^{-2} d^{-1} whereas the average CH_4 emission for the remaining part of the window was -0.03 g m^{-2} d^{-1}. The total CH_4 emitted from the window was 0.69 kg d^{-1} almost equally distributed between the two hotspots (see figure 6.9). The average CO_2 emission for the five hotspots varied between 7.41 to 619.65 g m^{-2} d^{-1} whereas the average CO_2 emission for the remaining part of the window was 0.46 g m^{-2} d^{-1}. The total CO_2 emitted from the window was 14.29 kg d^{-1}.

In general there was a good agreement between the location of the hotspots identified during the first campaign and the second campaign. Only one additional hotspot was identified during the second field campaign also located along the edge of the biowindow. However, the measured surface methane concentrations, hotspot areas and emissions were significant lower in comparison to the first field campaign. For example the total emission of CH_4 and CO_2 from the biowindow during the first campaign was 11.6 kg d^{-1} and 143.43 kg d^{-1} respectively in comparison to this campaign after compost excavation where the CH_4 and CO_2 emissions were measured to 0.69 kg d^{-1} and 14.29 kg d^{-1}, respectively. This was surprising as higher emissions were expected as the compost layer has been removed and thereby also the potential of reducing the methane emission by methane oxidation.

As the weather report showed that the measurements during the second campaign were conducted during a small increase in barometric pressure and might have resulted in an underestimation of the emissions is was decided to repeat the measurements two days after under more stable weather conditions.

Table 6.5. Ambient methane concentrations and methane and carbon dioxide emissions measured at hotspot areas on window 7 during the first December 2008 field campaign after excavation of compost material. Table also shows the four areas in which the different hotspots were found.

Location	Ambient methane conc.	Methane emission	Carbon dioxide emission	Methane fraction of total emission	Carbon dioxide fraction of total emission	Area
	ppmv	g m^{-2} d^{-1}	g m^{-2} d^{-1}	%	%	
7HS1	39,8	2,27	19,36	24	76	Area 1
7HS2	98,4	93,51	575,44	31	69	Area 1
7HS3	11,7	14,97	784,75	5	95	Area 2
7HS4	44,8	43,45	2.000,60	6	94	Area 2
7HS5	7,6	7,30	99,53	17	83	Area 2
7HS6	4	3,39	89,68	9	91	Area 2
7HS7	2,6	2,44	123,68	5	95	Area 2
7HS8	2,1	-0,03	0,12	0	100	Random
7HS9	2,5	-0,01	0,91	0	100	Random
7HS10	3,3	-0,06	0,38	0	100	Random
7HS11A	2	-0,01	0,43	0	100	Random
7HS11B	3,1	0,03	0,73	9	91	Area 3
7HS12	5,1	0,11	0,71	30	70	Area 3
7HS13	10,7	30,13	33,37	71	29	Area 3
7HS14	10,3	0,10	0,84	25	75	Area 3
7HS15	12,9	0,39	1,06	50	50	Area 3
7HS16	57	4,07	8,03	58	42	Area 3
7NS17	5,7	13,26	467,69	7	93	Area 4
7HS18	13,5	22,84	644,88	9	91	Area 4
7HS19	23	11,65	890,38	3	97	Area 5
7HS20	72	104,70	845,46	25	75	Area 5
7HS21	9,6	25,26	336,53	17	83	Area 5
7HS22	11,2	-1,04	95,15	0	100	Area 5
7HS23		0,06	10,80	2	98	Area 4

Table 6.6. Average methane and carbon dioxide emissions from hotspot areas on window 7 during the first December 2008 field campaign after excavation of compost material. Table also shows the emissions from the remaining area of the biowindow excluding the hotspots where surface flux measurements were made randomly.

Location	No. of flux measure-ments in area	Area of hotspot	Average methane emission	Total methane emission	Average carbon dioxide emission	Total carbon dioxide emission
		m^{-2}	g m^{-2} d^{-1}	kg d^{-1}	g m^{-2} d^{-1}	kg d^{-1}
Area 1	2	3,4	47,89	0,16	297,40	1,01
Area 2	5	11,2	14,31	0,16	619,65	6,94
Area 3	6	12,48	5,80	0,07	7,41	0,09
Area 4	3	1,8	18,05	0,03	556,29	1,00
Area 5	4	8,415	35,15	0,30	541,88	4,56
Random	4	1492,7	-0,03	-0,04	0,46	0,68
Total			sum	**0,69**		**14,29**

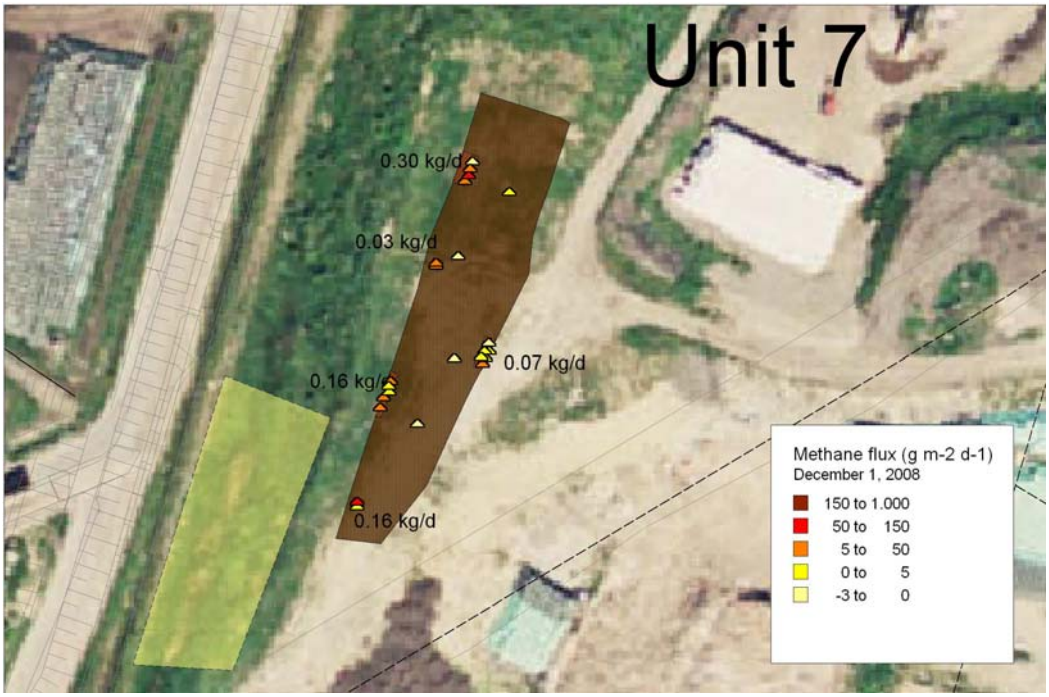


Figure 6.9. Methane emissions (g m^2 d^{-1}) measured at biowindow 7 at Fakse landfill during the first December 2008 field campaign after excavation of compost material. Five areas exhibiting high emissions were identified and the total methane emitted (kg d^{-1}) from the individual areas determined.

Table 6.7 shows the ambient methane concentrations measured during the second field campaign on window 7 after having removed the compost layer whereas Table 6.8 lists the average CH_4 and CO_2 flux from the five hotspots and the remaining area of the biowindow, where random flux measurements were made. Figure 6.10 shows the methane emissions (g m^2 d^{-1}) and the amount of methane emitted measured at window 7 at Fakse landfill.

The surface screening showed ambient methane concentrations ranging from background concentrations around 2 ppmv up to 98 ppmv. Based on the surface screening five areas with elevated methane concentrations were identified. The five areas varied in size from 1.8 to 12.48 m^2.

A good agreement between the locations of the hotspots identified during the previous campaign and this campaign. The measured surface methane concentrations, hotspot areas and emissions were a little higher in comparison to the previous field campaign.

All hotspot areas had increased by up to 200% (compare table 6.6 and table 6.8). Also the average CH_4 emissions for the individual hotspots were in general higher (15.92 to 43.64 g m^{-2} d^{-1} compared to 5.80 to 47.89 g m^{-2} d^{-1}). The total emission of CH_4 and CO_2 from the biocover window during the first campaign was 0.69 kg d^{-1} and 14.29 kg d^{-1} respectively in comparison to this campaign where the CH_4 and CO_2 emissions were measured to 3.26 kg d^{-1} and 73.36 kg d^{-1}, respectively.

The higher emissions measured during the second campaign clearly indicated that change in barometric pressure have an effect on the surface emissions from the excavated biowindow. A decrease in barometric pressure resulted in an increase in the overall methane emission of 4 times.

The overall emission is however still surprisingly low (3.26 kg CH_4 d^{-1} and 73.36 kg CO_2 d^{-1}) in comparison to the emissions measured from the compost surface in the first field campaign (11.63 kg CH_4 d^{-1} and 143.43 kg CO_2 d^{-1}). The average methane load to the compost biowindow is 2 g CH_4 m^{-2} d^{-1}, which is very low and significantly lower than the projected load of approximately 150 g CH_4 m^{-2} d^{-1} (Pedersen et al., 2008). The results show that the methane is not distributed equally to the compost window and mainly occurs through small hotspot areas along the edge (especially the western edge) of the biowindow. It is very clear that the gas distribution layer made of gravel is not working. It is however possible that a smaller part of the methane is oxidized in the gas distribution layer. This is supported by the composition of the emitted gas in comparison to the composition of the gas generated in the waste. In the gas emitted from the surface of the gravel layer methane makes up 21% whereas in the gas generated in the landfill methane makes up almost 55%. Hopefully analysis of the stable carbon isotopes in the methane emitted from the surface of the gas distribution layer compared to the generated methane will elucidate this. Samples for isotopic analysis were taken from flux chambers during both campaigns after excavation of the biowindow.

Overall it is very likely that the methane load to the gas distribution layer is too low indicating that the contact between the gas distribution layer and the waste volume is insufficient. This is most likely due to a combination of daily cover with clayey soils and compaction of the disposed waste both enhancing horizontal gas transport leading to side emissions through the slopes of the waste cell. This was confirmed by emission measurement of the western slope of the waste disposal site (see section 4.2).

Table 6.7. Ambient methane concentrations and methane and carbon dioxide emissions measured at hotspot areas on window 7 during the second December 2008 field campaign after excavation of compost material. Table also shows the four areas in which the different hotspots were found.

Location	Ambient methane conc.	Methane emission	Carbon dioxide emission	Methane fraction of total emission	Carbon dioxide fraction of total emission	Area
	ppmv	g m^{-2} d^{-1}	g m^{-2} d^{-1}	%	%	
7HS1	315					Area 1
7HS2	5	22,64	737,63	8	92	Area 1
7HS3	83	3,65	174,26	5	95	Area 2
7HS4	292	50,61	1.793,57	7	93	Area 2
7HS5	18	0,49	64,79	2	98	Area 2
7HS6	51	50,16	844,38	14	86	Area 2
7HS7	15	113,29	2.313,35	12	88	Area 2
7HS8	2					Random
7HS9	2					Random
7HS10	2,5	-0,01	0,68	0	100	Random
7HS11A	2	-0,06	-1,18	0	100	Random
7HS11B	2	0,28	1,38	36	64	Area 3
7HS12	3					Area 3
7HS13	16	75,59	233,84	47	53	Area 3
7HS14	9	0,16	0,96	31	69	Area 3
7HS15	25	0,93	3,87	40	60	Area 3
7HS16	21	2,99	10,60	44	56	Area 3
7NS17	11	49,83	1.750,32	7	93	Area 4
7HS18	228	58,98	2.426,68	6	94	Area 4
7HS19	20	11,18	855,58	3	97	Area 5
7HS20	3	66,81	308,41	37	63	Area 5
7HS21	5	-0,03	1,29	0	100	Area 5
7HS22	7	3,00	40,42	17	83	Area 5
7HS23	6	-0,02	1,53	0	100	Area 4
7HS24	8	0,09	4,26	5	95	Area 4
7HS25	330	108,67	2.143,97	12	88	Area 4

Table 6.8. Average methane and carbon dioxide emissions from hotspot areas on window 7 during the second December 2008 field campaign after excavation of compost material. Table also shows the emissions from the remaining area of the biowindow excluding the hotspots where surface flux measurements were made randomly.

Location	No. of flux measure-ments in area	Area of hotspot m^{-2}	Average methane emission g m^{-2} d^{-1}	Total methane emission kg d^{-1}	Average carbon dioxide emission g m^{-2} d^{-1}	Total carbon dioxide emission kg d^{-1}
Area 1	1	3,4	22,64	0,08	737,63	2,51
Area 2	5	20,7	43,64	0,90	1.038,07	21,49
Area 3	6	18,9	15,92	0,30	49,62	0,94
Area 4	5	30,6	43,51	1,33	1.265,35	38,72
Area 5	4	32,2	20,24	0,65	301,42	9,71
Random	4	1424,2	0,08	0,12	1,20	1,70
Total				**3,26**		**73,36**

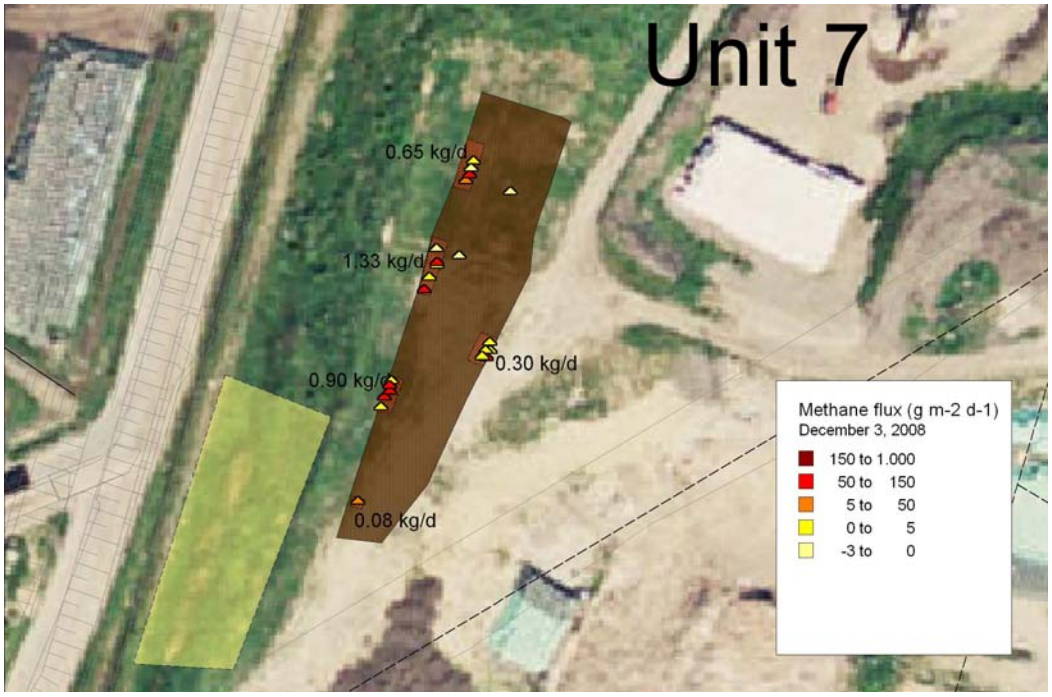


Figure 6.10. Methane emissions (g m^2 d^{-1}) measured at biowindow 7 at Fakse landfill during the second December 2008 field campaign after excavation of compost material. Five areas exhibiting high emissions were identified and the total methane emitted (kg d^{-1}) from the individual areas determined.

Based on the conducted field work the following conclusions regarding biowindow 7 can be drawn:

The total CH_4 emitted from the compost biowindow was 11.6 kg d^{-1} with the majority (5.1 and 6.1 kg d^{-1}) of the emission coming from two hotspots located close to the edge of the biowindow. The two hotspots had a total area of 108 m^2 making up less than 7% of the whole biowindow area. From the remaining surface area mainly negative methane emissions rates were obtained indicating oxidation of atmospheric methane. Overall the results show high spatial variability in emissions and indicate that methane emissions are related to smaller hotspots on the biowindow.

The total CH_4 emitted from the excavated window was 3.26 kg CH_4 d^{-1}, which is significantly lower than the projected methane load to the window (229 kg d^{-1}). In spite of the possibility that a part of the methane going to compost biowindow is actually oxidized in the gas distribution layer it is believed to be more likely that the gas generated within the waste body is not transported to the window. This is most likely due to a combination of daily cover with clayey soils and compaction of the disposed waste both enhancing horizontal gas transport leading to side emissions through the slopes of the waste cell.

Emissions measured on the surface of the gas distribution layer are limited to a few hotspots corresponding to the hotspots identified on top of the compost windows showing that gas generated within the waste is mainly going to smaller areas along the edge of the biowindow. Locations of the hot spot correspond well with the location of trenches dug out to enhance gas transport to the window. It is however clear that the gravel layer did not manage to distribute the gas coming from the landfilled waste body.

Several indications are seen on methane oxidation in both the gas distribution layer and in the compost material. Hopefully analysis of stable isotopes sampled in flux chambers positioned on the compost surface and the gravel layer will elucidate this.

7 Whole site emission and oxidation

Introduction and objective

In order to quantify the overall performance of the biocover system, baseline measurements of the whole methane emission before installation were compared to emission measurements after construction of the biocover system.

The whole methane emission from the disposal site was measured using a tracer technique, combining controlled tracer gas release from the landfill with time-resolved concentration measurements downwind the landfill using FTIR absorption spectroscopy. Initially to each release experiment a general leak search at the landfill was conducted with the main purpose to identify high emission areas for placement of the tracer release bottles. The dynamic plume measurement method is described in Scheutz et al., 2007.

Two field campaigns were performed; during October 11-12, 2006 and February 19-20, 2007 to quantify the methane emission from the site before installation of the biocover system. This was part of the baseline study reported in task 3 of the Biocover project. At both baseline field campaigns an overall leak search showed that the CH_4 emission from the old landfill section was localized to the leachate collection wells and slope areas. The baseline average CH_4 emission from the old landfill section was estimated to be 31.2±6.8 kg CH_4 h^{-1} in October 2006 and 30.5±2.2 kg CH_4 h^{-1} in February 2007, whereas the source at the new section was quantified to be 12.2±3.3 and 7.3±2.2 kg CH_4 h^{-1} in the October respectively February measurement. The results of the baseline study are described in detail in Scheutz et al., 2007.

Methodology

Field campaigns.

After installation of the biocover system four field measuring campaigns were carried out including whole site emission measurements and isotopic analysis of plume samples. The isotopic samples were being analyzed at time of writing this report, and results will be reported later. The field campaigns were generally planned so measurements were carried out under stable weather conditions where the measured emission is believed to be representative for the whole landfill emission rate at the particular season. Table 7.1 provides an overview of the weather conditions during the field campaigns. In general all campaigns were carried out under relative stable pressure conditions as only small changes in barometric pressure were observed during the period where the measurements were carried out. Only during the April campaign a more pronounced pressure decrease was observed in comparison to the other campaigns meaning that the obtained emissions might be overestimated in comparison to a situation with more stable weather conditions.

Tracer release and weather conditions during field campaigns.

<u>October 2007 campaign:</u>

The methane emission at Fakse landfill was measured with mobile FTIR and tracer release on the 16th and 17th of October 2007. During the measurements weather was cloudy, with a wind speed of about 3.5 ms^{-1} from the southwest. Barometric pressure was 1010 mbar in the morning, ending up at 1008 mbar at 19:00 in the evening, thus showing a small pressure drop during the measurement. The average daily

temperature was 10.6 °C. At the initial leak search prior to the emission measurement, the gas wells at the eastern border of the landfill were identified as a localized source. Also a gas well with a damaged sealing at the southwestern corner was found to emit methane. One tracer was put on the "new source" west of the composting area, and four tracers were distributed on the old landfill section, in order to identify the emission from these areas separately. The overall tracer release was 11.7 kg h^{-1}. Samples for isotopic analysis were taken from the plume of the old section (9 samples) and the new section (4 samples). I addition background samples (5 samples) and samples of the raw gas generated within the waste were taken (5 samples).

April 2008 campaign:

The methane emission at Fakse landfill was measured with mobile FTIR and tracer release on the 1st of April 2008. Weather was broken skies with wind from southeast at 3-4 ms^{-1}. The barometric pressure was 1009 mbar. The average daily temperature was 10.4 °C. Five N_2O tracers were used at the experiment, all set at the same release rate, giving a total release rate of 11.7 kg h^{-1}. Four tracers were distributed at the old section, and one tracer was put centrally on the new part. Six plume samples for isotopic analysis were taken in position (55.234010ºN, 12.086423ºE) downwind the site at 19:15-19:30 080401, in a plume having about 250-450 ppbv excess CH_4 above ambient. Four background samples were taken in position (55.226893ºN, 12.112042ºE).

August 2008 campaign:

The methane emission at Fakse landfill was measured with mobile FTIR and tracer release on the 8th of August 2008. The average daily temperature was 18.0 °C. The emission measurements were done at westerly winds, and thus the measured emission is made up of both contributions from the old section, the new section and the compost area. The leak search looked similar to previous occasions where the emission partition between the old and new part has been about 80% respectively 20%.

December 2008 campaign:

The methane emission at Fakse landfill was measured with mobile FTIR and tracer release on the 3rd and 4th of December 2008 also including leak search with an infrared narrow band camera for methane detection. The old part of the landfill site had been covered with a final layer since the August measurements. The "hot areas" were located to the mid northern side of the old section, at the slope including a leaking gas well (verified with camera). Also the gas wells in the middle of the old section, close to the easternmost tracer position were identified with an infrared camera, showing several leaks through the cap. The western slope of the old section showed some emissions also this time, as well as the gas well close to entrance balance. The average daily temperature was 2.4 °C. The barometric pressure were below normal, around 990-994 mbar during the measurements, and during the tracer experiment the wind was somewhat changing, coming from the southeast to east, thus making it possible to separate the old section plume from the new, and sometimes not. Five N_2O tracers were used at the experiment, all set at the same release rate, giving a total release rate of 11.7 kgh^{-1}. Four tracers were distributed at the old section, and one tracer was put centrally on the new part. Five air samples for isotopic analysis were taken on the old site and one sample from the new section. Five background

samples were taken in position (55.228087ºN, 12.083428ºE) upwind the site at 14:20 081204.

Table 7.1. Overview of the weather conditions during the conducted field campaigns. Data were obtained from Brandelev weather station.

Date for plume measurements	**Time interval for plume measure-ments**	**Baro-metric pressure during the measurements** mbar	**Change in barometric pressure 24 and 12 hours before and after campaign** mbar	**Overall pressure obser-vation**	**Average tempera-ture during campaign** °C	**Average wind speed during campaign** m s^{-1}
October 12th 2006	12:10 – 17:40	1021.4-1024.9 (Δ3.5)	24 h: 12.4 12 h: 8.9	Small pressure increase	15.1	5.4
February 20th 2007	18:40 – 22:30	1014.0-1016.2 (Δ2.2)	24 h: -1.7 12 h: 4.1	Small pressure increase	3.1	3.3
October 17th 2007	16:30 – 18:10	1009.7-1009.6 (Δ-0.1)	24 h: 6.4 12 h: -0.9	Between a small pressure decrease and increase	10.6	2.7
April 1st 2008	17:45 – 19:00	1016.0-1014.4 (Δ-1.6)	24 h: -5.3 12 h: -9.4	Pressure decrease	10.4	4.3
August 8th 2008	8:00 – 9:10	999.4-999.7 (Δ0.3)	24 h: -2.9 12 h: 6.5	Small pressure increase	18.0	4.6
December 4th 2008	9:50 11:50	997.6-996.4 (Δ-1.2)	24 h: -7.5 12 h: -9.9	Between a small pressure increase and decrease	2.4	3.0

Results

Table 7.2 gives and overview of the methane emission measured during the four campaigns.

During the October 2007 trial, the CH_4 emission from the old landfill area was measured to be 36.0 ± 2.0 kg CH_4 h^{-1} (± 1 STD, 6 traverses), while the western source at the new section was found to emit 11.5 ± 3.5 kg CH_4 h^{-1} (7 traverses). The emission was quit comparable to the emissions measured at the two previous campaigns during the baseline study before installation of the biocover system. It is possible that the emission is a little higher than expected under stable atmospheric conditions as a small pressure decrease (1010 mbar in the morning, ending up at 1008 mbar in the evening) was recorded during the campaign. The initial leak search prior to the emission measurement showed that leachate collection wells at the eastern border of

the landfill were emitting methane. Also a leachate well with a damaged sealing at the southwestern corner was found to emit methane. Overall the measurement campaign showed that the establishment of the biocover system had not reduced the overall emission from the site partly as different sources like the leachate collection wells were still emitting methane.

During the April 2008 trial, the emission from the old and new section could be separated, and it was found that the old section emitted 36.7±3.4 kg h^{-1}, and the new 9.1±2.0 kg h^{-1}. The measurements of the new section had to be done quite closely on the main road (209), and thus have a higher uncertainty and spread than the distant measurements of the old sections emission.

During the August 2008 campaign, the emission measurements were done at westerly winds, and thus the plumes from the old and the new section could not be separated. The measured emission therefore includes both the contributions from the old section and the new section. However, as the initial leak search looked similar to other campaigns the emission partition between the old and new section could be estimated to about 80% respectively 20%. The total methane emission was 34.3±2.5 kg h^{-1} with 27.4 kg h^{-1} and 6.9 kg h^{-1} coming from the old and the new section respectively.

During the December 2008 campaign, the emissions from the old section seem lower, about 22±5 kgh^{-1}, whereas the new section was measured to have an emission of 6±1.8 kgh^{-1}. The total emission transects including both the old and the new section and the compost area, showed an emission of 31.1 kg h^{-1}. Despite the lower barometric pressure, which will normally give rise to an overestimation of the emission, the methane emission from the old section was lower than earlier campaigns.

Table 7.2. CH_4 emission (kg h^{-1}) from the old landfill section (section I) and the new section (Section II).

Field campaign		Old landfill section (Section I)	New landfill section (Section II)
Baseline			
October 2006	Time interval	12:10 - 16:30	16:00 - 17:40
	Traveses	26	7
	Average ± STD	31.2 ± 6.8	12.2 ± 3.3
February 2007	Time interval	18:40 - 22:30	18:40 - 22:30
	Traveses	8	12
	Average ± STD	30.5 ± 2.2	7.3 ± 2.2
After installation of biocover system			
October 2007	Time interval	16:30 - 18:10	16:30 - 18:10
	Traveses	6	7
	Average ± STD	36.0 ± 2.0	11.5 ± 3.5
April 2008	Time interval	17:45-1844	17:45-19:09
	Traveses	7	10
	Average ± STD	36.7±3.4	9.1±2.0
August 2008	Time interval	8:02 – 9:10	8:02 – 9:10
	Traveses	11	11
	Average ± STD	27.4±2.5	6.9±2.5
December 2008	Time interval	9:53 – 11:33	9:53 – 11:50
	Traveses	4	7
	Average ± STD	22.2±4.6	6.0±1.8

The average baseline methane emission before installation of the biocover system was 30.9 kg h^{-1} and 8.5 kg h^{-1} from the old and the new landfill section, respectively.

During the following two campaigns conducted in October 2007 and April 2008 a little higher methane emission of 36.4 kg h^{-1} from the old section and 10.3 kg h^{-1} were seen. It is likely that the emission measured during April 2008 was high since this campaign was performed during decrease of atmospheric pressure.

The last two campaigns conducted in October 2008 and December 2008 both showed significantly smaller emissions in comparison to the baseline study. The emission from the old section was measured to be 22.0 indicating an overall reduction of 9 kg h^{-1} corresponding to 29% in comparison to the baseline study.

8 Discussion

Constructing a full scale biocover system in Fakse landfill posed several unforeseen challenges. Baseline measurements of total methane emission and emission from local sources showed a much larger than anticipated methane emission from the site, and thereby a need for a biocover system with a much higher methane oxidation capacity. The baseline study also showed that the leachate collection system was a very important pathway of landfill gas emission from the site, and since the gas had to pass through biocover windows for the system to work modifications to the leachate collection system were needed.

At the site, low permeable clayey soil was used for final and temporary covering of the waste. This has led to a complicated flow pattern of the landfill gas from the waste, where it is produced to the atmosphere. When installing the biowindows, clayey soil was often seen to be mixed with the waste beneath the soil cover, which can explain difficulties of obtaining a high enough load to the windows without important leaks such as the leachate drainage system. After installing caps to prevent leaks through wells at the site, gas was measured to emit from the leachate pumping station instead. After installing water locks at the pumping station to counter this leak, gas was seen to emit through the soil surface immediately near the leachate wells.

Another factor which was shown to be important was an uneven spatial distribution of methane load to the biowindows. These were for example seen, where t trenches were dug to increase the load to window 7. Since methane was observed to emit at quite high rates through hot spots in the biowindows, it can be concluded that parts of the biocover system was overloaded. The studies of gas transport and oxidation of the windows 1.1 and 7 did show an inhomogeneous flow of landfill gas to the windows with areas of little or no load, and other areas of loads higher than the methane oxidation capacity of the compost previously measured as a part of this project.

Significant methane oxidation, and thereby reduction of greenhouse gas emission was, however, observed at Fakse landfill. Several types of measurements performed points to this conclusion:

- Measurements of total methane emission from the site described in chapter 7 did show lower methane emissions after the improvements of the system described in chapter 3. The measurements suggests an overall methane emission reduction by approximately 30%
- Measurements of spatial variability in emissions described in section 4.2 showed that significant amounts of landfill gas was passing through the biocover windows
- Gas concentration profiles from biocover windows (chapters 2 and 4) show that methane oxidation was taking place in the biocover material
- Carbon balance calculations on surface flux measurements of methane and carbon dioxide taking into account carbon dioxide production by respiration in the compost material suggests methane oxidation in the biowindows

Interestingly, from a process understanding point of view, gas profiles suggest methane oxidation occurred to some extend before landfill gas passing through the biowindows. An explanation for this can be oxidation of methane in the root blocking gravel/gas distribution layer or the top parts of the waste material. Since oxygen is needed for biological methane oxidation to take place, and that landfill gas is anaerobic, oxygen supply from the atmosphere is necessary for this to take place. Emission dynamics, caused by changes in atmospheric pressure, is a plausible explanation for this. The relatively low landfill gas emission at Fakse landfill was seen to vary to a large extent according to rise and fall of atmospheric pressure. During rise of pressure, influx of atmospheric air, and thereby oxygen, through parts of the biocover windows to the gas distribution layer and waste material is possible.

Lab studies on respiration in the compost material as well as field measurements did show that the carbon dioxide production caused by respiration is significant by value. This means that there is a risk of overestimating methane oxidation in compost biocover systems, if the methane oxidation rate is based solely on flux measurements of methane and carbon dioxide. Even if the landfill gas load is zero, carbon dioxide emission will occur due to production in the compost. The higher the load, the lower is the respiration since landfill gas advective flow prevents the diffusion of oxygen into the compost matrix and therefore aerobic respiration of the compost is diminished.

Accurate determination of methane load to the biowindows was difficult. Using the deep flux chambers designed for this use did not yield reliable results. The most reliable data produced in this study to determine the overall efficiency of the biocover system installed was measurements on total methane emission from the site using tracer release and downwind measurements.

9 Conclusion

Evaluation of the methane oxidation performance of the biocover system was done both for the whole system, and in more detail on selected biowindows. Performance of whole landfill emission measurement using the tracer method also applied to obtain the baseline emission previous to the biocover system establishment. Comparing the baseline emissions to the final emissions showed that the overall biocover performance was about a 30% reduction in methane emissions, after improvements to the system were made as result of initial performance testing. The number is uncertain due to barometric pressure changes affecting the total emission at the time of measurement. Most measurement was done at stable weather conditions to avoid this effect. It is recommendable to perform several measurements (more than five) of the total emission both before (baseline) and after biocover system establishment.

The overall performance may also be based upon measurement of changes in stable isotope ratios in methane. This method was used at the site but the results are pending and will be included in after-LIFE articles.

Significant leaks of the system were found. Most notably was the leachate collection system in spite of several initiatives to reduce emission through this pathway. It is obvious that the way leachate collection systems are made on modern landfills creates a conflict for the gas management at the sites.

An uneven landfill gas load to the biowindows was seen, which was likely due to a low permeability of the waste mass as a result of mixing with clayey soils. The uneven gas load created hot spots within the biowindows with low gas retention times resulting in significant methane emissions from these locations – despite of high methane oxidation properties of the compost in these areas.

The methane oxidation rates in the biowindows were determined by a carbon mass balance. An important factor in such a mass balance is the carbon produced by normal oxidation of the compost material (respiration). To get reliable predictions of the methane oxidation rates, independent determination of the compost respiration is needed.

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Appendix 1: Equipment

Exetainer vials

Storing of gas samples taken in the field was done in Labco Exetainer 5.9 ml evacuated flat bottomed soda glass vials fitted with pierceable rubber septa.

FID

A Photovac MicroFID portable flame ionization detector (FID) was used for field measurements of methane concentrations. The lower detection limit of this instrument was 0.5 ppmv methane. Accuracy of the instrument was specified to be +/- 0.5 ppmv or +/- 10% of actual methane concentration (0.5 to 2000 ppmv range). Concentrations were measured every second with concentrations displayed in real time on the instrument, and logged on the instrument. Calibration was done daily at 0 and 500 ppm CH_4

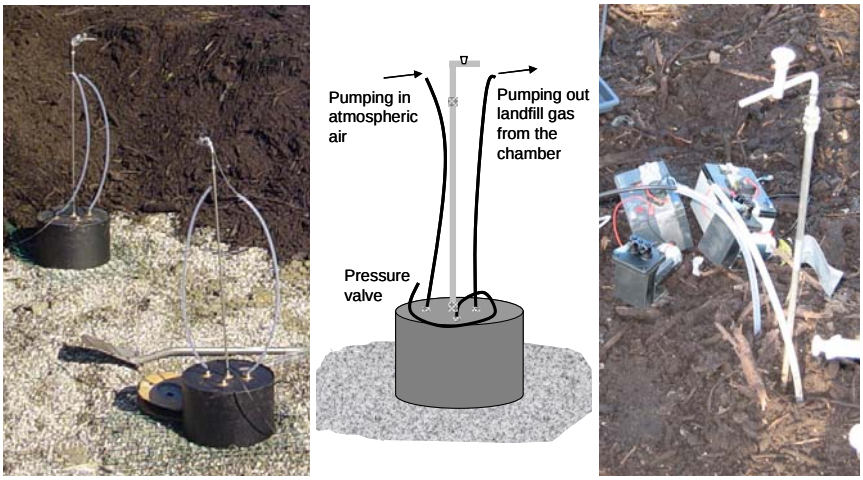
Flux chambers (surface emission measurements)

A 15.5 liter stainless steel flux chamber fitted with a manually operated fan for stirring was used for measurement of gas flux through the surface of biowindows and soil cover at the landfill. Concentrations of methane and carbon dioxide were measured using an Innova gas monitor or FID and NDIR detectors.

Flux chambers ("deep chambers" to measure LFG load to biowindows)

The deep flux chambers were made of lacquered steel and have a height of 24cm and a diameter of 28.5cm and were equipped with two 6*4mm PE tubing that reached the surface and allows for flushing the chamber with atmospheric air prior to the flux measurements (see figure below). The chambers were equipped with manually operated fans. Flushing was done with two air pumps: one pumping in atmospheric air to the chamber at a rate of 17 L min^{-1} and one pumping out air from the chamber at the same rate.

After flushing, increase of concentrations of methane and carbon dioxide was measured using the Innova gas monitor, while stirring the air inside the chambers.



From left: Deep flux chambers in place on gas distribution layer; Drawing of the deep flux chamber; flushing; Above ground in the field, flushing is disconnected and the Innova is connected to one of the tubes.

Gas concentration probes

Gas concentration probes were made of 1.5m long ordinary water pipe, closed in both ends, where 10 cobber pipes (3*4mm) with different lengths were sounded onto, closed in the lower end and provided with 5 2mm slots for drawing gas samples. Sample slots were placed in 100cm, 80cm, 60cm, 50cm, 40cm, 30cm, 20cm and 10cm provided that the probe were set down with 40cm above ground. Above ground the cobber tubes were sealed with silicone tubing and 5ml syringes. Two times 5ml was drawn prior to sampling.

For each measurement campaign the height of the probe was measured to ensure that the right depths were achieved for the gas concentration profile and to evaluate the compaction of the compost material.

GPS

A Trimble 5700 RTK GPS with TSC1 controller was used to measure positions of gas sampling, flux measurements, location of biowindows etc. Locations were measured with an accuracy of 2 cm or better.

Innova gas monitor

An Innova 1312 photoacoustic multi gas monitor was used to measure concentrations of methane and carbon dioxide. Concentrations and times of measurement were logged using a laptop pc connected to the instrument. Measurement ranges at the used configuration of the instrument were 0.4 – 20,000 ppm (methane) and 1.5 – 10.000 ppm (carbon dioxide). A rate of circa one measurement per minute was possible.

Protection against liquid water: UA1365 In-line Genie membrane separator.

MicroGC

The Chrompack Micro GC CP-2002P gas chromatograph was equipped with a thermal conductivity detector and two columns. Oxygen and nitrogen is quantified on a 4 m long Molsieve 5A column and methane and carbon dioxide on a 10 m long Poraplot Q column. Carrier gas is helium, and the column temperature is 40°C. Gas standards produced by MicroLab, Aarhus, Denmark ranging from 0.02 to 100 % v/v were used for calibration.

The MicroGC was controlled using CP Maitre Elite software, and was fitted with a battery for field use.

NDIR CO_2 detector

A Vaisala GMP343 CO_2 probe & GM70 control unit for certain measurements of CO_2 concntrations. The instrument is a silicon based, non dispersive infrared (NDIR) sensor.GMP343 was calibrated using ±0.5 % accurate gases at 0 ppm, 200 ppm, 370 ppm, 600 ppm, 1000 ppm, 4000 ppm and 2 %. Calibration is also done at four temperature points, -30 °C, 0 °C, 25 °C and 50 °C.

Measurement range: 0 – 5000 ppm CO_2

Response time (90%): 82 seconds.

Accuracy (excluding noise) at 25 °C (77 °F) and 1013 hPa after factory calibration with 0.5 % accurate gases with different range options: ±(5 ppm + 2 % of reading)

Thommen HM35 handheld digital pressure gauge

Differential pressure range: 0 – 25 mbar

Error limit = 0.1% * 25mbar = 0.025 mbar

Appendix 2. Evaluation of deep flux chamber performance

The performance of the deep flux chambers is evaluated based the results in table 2.1 and the corresponding results for the deep flux chambers. The carbon mass balance (CO_2 plus CH_4 fluxes) is seen in figure 2.4A, B and C for Nov 07, Dec 07 and Jan 08. It is very clear that a disappearing little part of the presumed load to the biocover window is emitted on the surface which is physically impossibly. If the loads found in the deep flux chambers are true the assimilation is above 90% in 31 out of 36 results and this is very unlikely. Therefore it can be assumed that the load found with the deep flux chambers is not true.

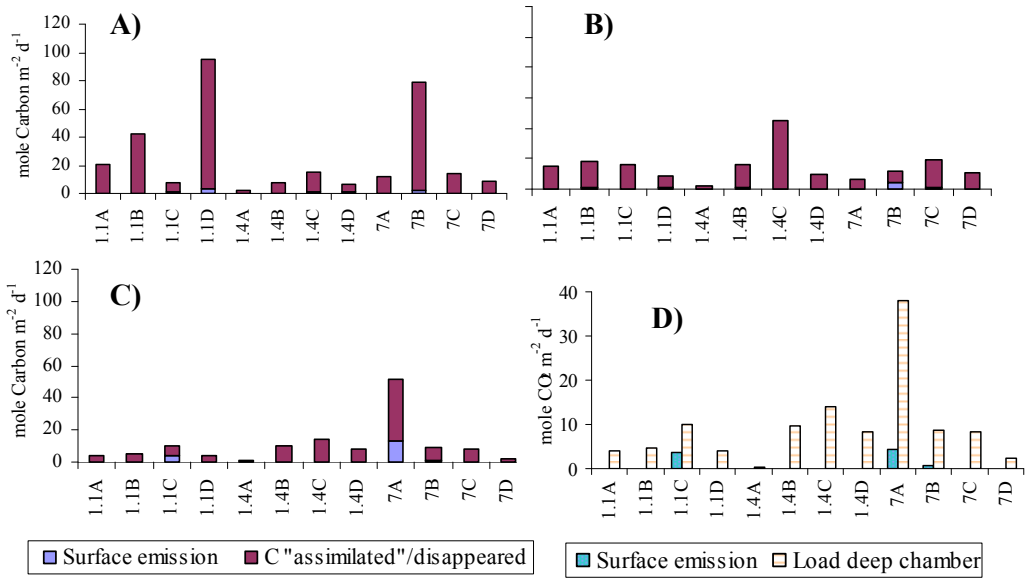


Figure 2.4. Carbon mass balance for the deep flux chambers. The surface emission added with the "assimilated" carbon corresponds with the load to the deep flux chambers. A) Results from Nov 07, B) Results from Dec 07, C) Results from Jan 08. D) Carbon dioxide mass balance for Jan 08.

The simplest way to get to this conclusion is looking at the carbon dioxide fluxes (Figure 2.4D). Carbon dioxide cannot disappear from the system to a great extent, only by dissolution into percolating rainwater. Therefore the surface emission of carbon dioxide should be higher or identical with the load of carbon dioxide (figure 2.4D). It is clear that there is a severe problem with the method, as carbon dioxide should not disappear from the system.

One possible reason for this is that the deep flux chambers function as a funnel for the landfill gas if there is a capillary barrier in the bottom of the compost. Moist conditions in the bottom of the compost have been seen in several occasions when compost has been dug out of the filter. One solution to this problem could be to shut of the pressure valve though risking a pressure build up in the chamber, or put the deep flux chamber over the capillary barrier, e.g. 20-30cm above the gas distribution system.

Appendix 3: Uncertainty of mass balance approach: Respiration and Assimilation

Objective

The determination of the load by the deep flux chamber measurements were found insufficient and very few stable isotopic measurements were done so the only way to determine load and methane oxidation was by using a simple mass balance approach. Though the uncertainties of the influence of respiration of the compost it self can manipulate the results. Therefore it was decided to investigate further the compost respiration in columns not charged with landfill gas, which is presented in Chapter 6.

Furthermore a second look was taken on results from the Task 4 report (Pedersen et al 2008) to try to get an idea of the respiration of a compost column charged with landfill gas and to evaluate the development of assimilation and respiration as the methanotrophic populations grows over time. Additionally results for all investigated compost materials were presented as this could give an idea of whether the development seen were material specific or related to the development of the methanotrophic population.

Method

Beneath is given an overview of the possible emission of carbon dioxide related to

1) Methane oxidation and 2) Respiration of organic matter. Continuously growth and decay of methanotrophic bacteria (and other soil bacteria) will go on and therefore both bacterial respiration and compost respiration are possible sources of carbon dioxide, but having a stable methanotrophic community it should be plausible to assume that growth equals decay (assimilation equals bacterial respiration). Though if a compost is charged with landfill gas over a long period and then taken to the lab for investigating compost respiration the respiration will most likely be overestimated as the carbon indirectly originates from methanotrophic respiration (decay of the methanotrophic community)

$$CH_{4,aq} + O_{2,aq} = CO_{2,CH_4} + H_2O + C_{ass} + heat + CO_{2,bacterial\_respiration} \qquad \Delta G=-780 kJ/mol\ CH_4$$

$$C_{soil,org.matter} + O_2 = CO_{2,soil\_respiration} + H_2O \qquad \Delta G= ????kJ/mol\ CH_4$$

The term CH_2O, the simplest carbohydrate, is useful geochemical shorthand for generic plant tissue; actual plant materials contain substantial nitrogen as well as a large number of minor and trace elements.

The terrestrial carbon cycle is completed by respiration (Selker et al 1999)

$CH_2O+O_2 \rightarrow CO_2+H_2O$ (Selker et al 1999)

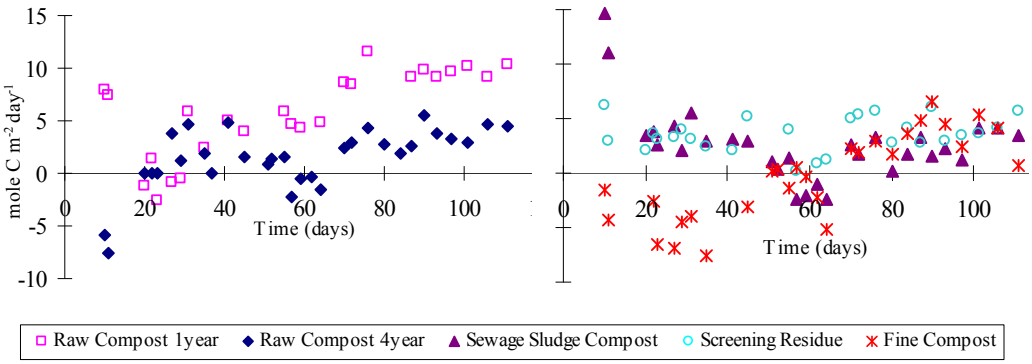


Figure 1. Soil respiration in column experiments from Task 4: Testing Improvement Strategies (Pedersen et al. 2008). Calculated as excess carbon emitted as CO_2 assuming steady state for the methane oxidation (decay equals growth), which will most likely not be the case in the beginning of the experiment but could be expected in the end.

In Figure 1 the soil respiration in column experiments from Task 4: Testing Improvement Strategies is seen for all the 5 materials tested. The soil respiration is calculated as excess carbon emitted as CO_2 assuming steady state for the methane oxidation (decay equals growth), which will most likely not be the case in the beginning of the experiment, as the methanotrophs build up a population, but it could be expected to be true in the end of the experiment. In figure 2.5A it seems like excess carbon reaches a steady level after app. day 70 For both RC1 and RC4 and the soil respiration for the younger raw compost (1year) is higher than for the older one (4years) which is as expected.

In Figure 2.5 the increase of the carbon excess over time in the system could be controlled by decreasing assimilation as it should app. zero as a steady state occurs. It is not suspected that respiration of the soil will increase as oxygen penetrates lower and lower into the soil matrix. Though it can also be bacterial respiration (decay) if the bacterial population has reached its max (due to e.g. nutrient limitation) and is dying off to reach a stable and lower level. Looking at the results for all 5 materials it can be concluded that the excess carbon dioxide emission is material specific and not related to the size of the methanotrophic population. The methanotrophic population should be bigger in RC4 than in RC1 as it has higher methane oxidation rate (108 g m^{-2} day^{-1}) than RC1 (52 g m^{-2} day^{-1}) (Pedersen et al 2008). The negative soil respiration seen for the fine compost (Figure 2.5B) must reveal that the assimilation is bigger than the respiration in the beginning of the experiment.

In Table 2.3 the average soil respiration values for the 5 tested soils can be seen. The average soil respiration for the 4year old raw compost, which is used in the biocover windows were 1.7 mole m^{-2} day^{-1} (250g m^{-2} day^{-1}). This is a rather high number compared to the carbon dioxide emission rates reported in Table 2.2 though soil respiration is highly temperature dependent. Q_{10} values between 2.2-4.2 has been found for a temperate peat bog (Lafleur et al 2005 and Schindbacher et al 2008) Using a Q_{10} value of 3 the respiration for the raw compost 4year old will be 0.6 mole m^{-2} day^{-1} and 0.2 mole m^{-2} day^{-1} for 12°C temperature of the compost and 2°C temperature of the compost respectively. The temperature dependency for the Task 4 respiration and the Chapter 6 respiration can be seen in figure 2

Table 1: Respiration and assimilation parameters for the compost types tested in Task 4 (Pedersen et al. 2008)

Experiment	*Parameter*	*Unit*	*RC1*	*RC4*	*SC*	*SR*	*FC*
Column	CO_2 prod.	mole CO_2 m^{-2} day^{-1}	5.7	**1.7±3.1**	2.7	3.5	-0.3
	O_2/ CH_4		3.5	2.0	2.2	2.9	1.5
	CO_2/ CH_4		2.8	1.3	1.4	2.3	1.0
	Bulk density	kg/m3	356.1	486.6	330.6	286.7	505.4
		kg/column	10.06	13.75	9.34	8.10	14.28
Batch	O_2 prod.	µmole O_2/g dry soil/h	1.95	0.12	3.82	2.97	1.09
	CO_2 prod.	µmole CO_2/g dry soil/h	1.66	0.10	3.30	1.11	0.75
	O_2 prod[a]	mole O_2 m^{-2} day^{-1}	5.0	0.4	9.1	6.1	4.0
	CO_2 prod.[a]	mole CO_2 m^{-2} day^{-1}	4.3	0.3	7.9	2.3	2.7
	Assimilation	mole C m^{-2} day^{-1}	-1.4	-1.3	5.2	-1.2	3.0

[a] Calculated assuming that 1/3 of the column respires.

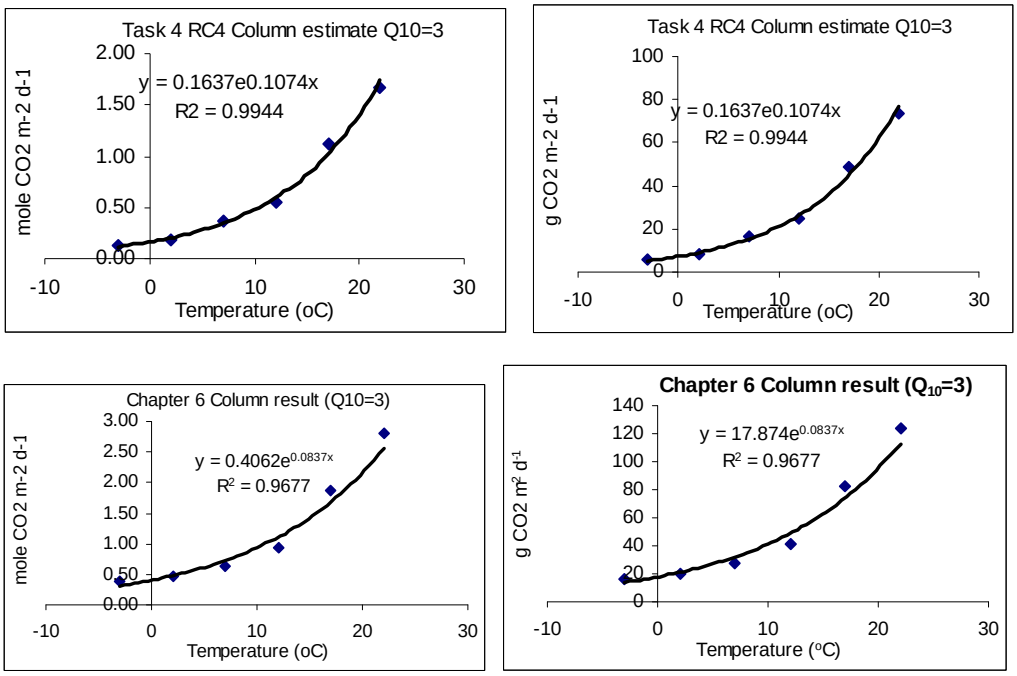
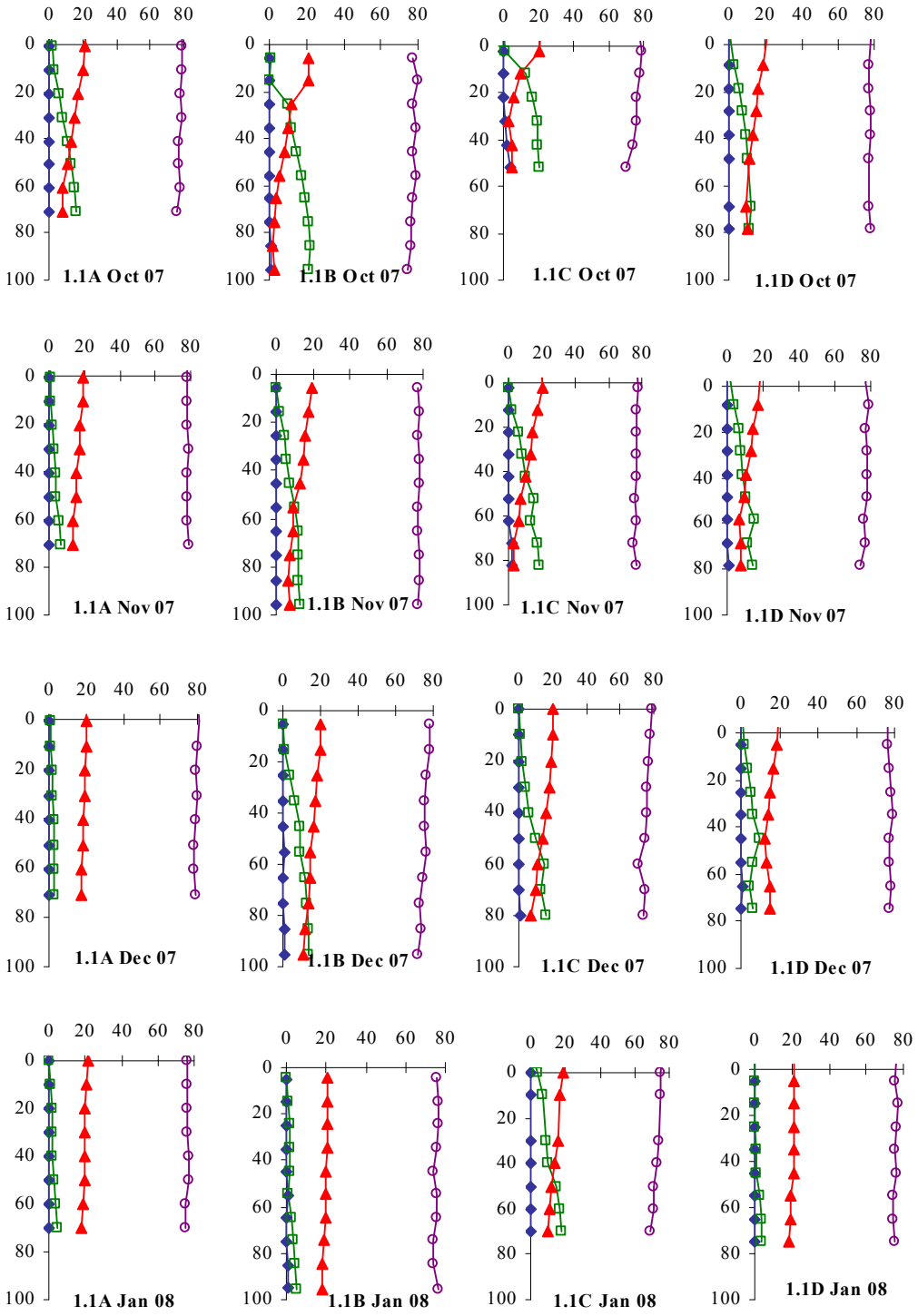


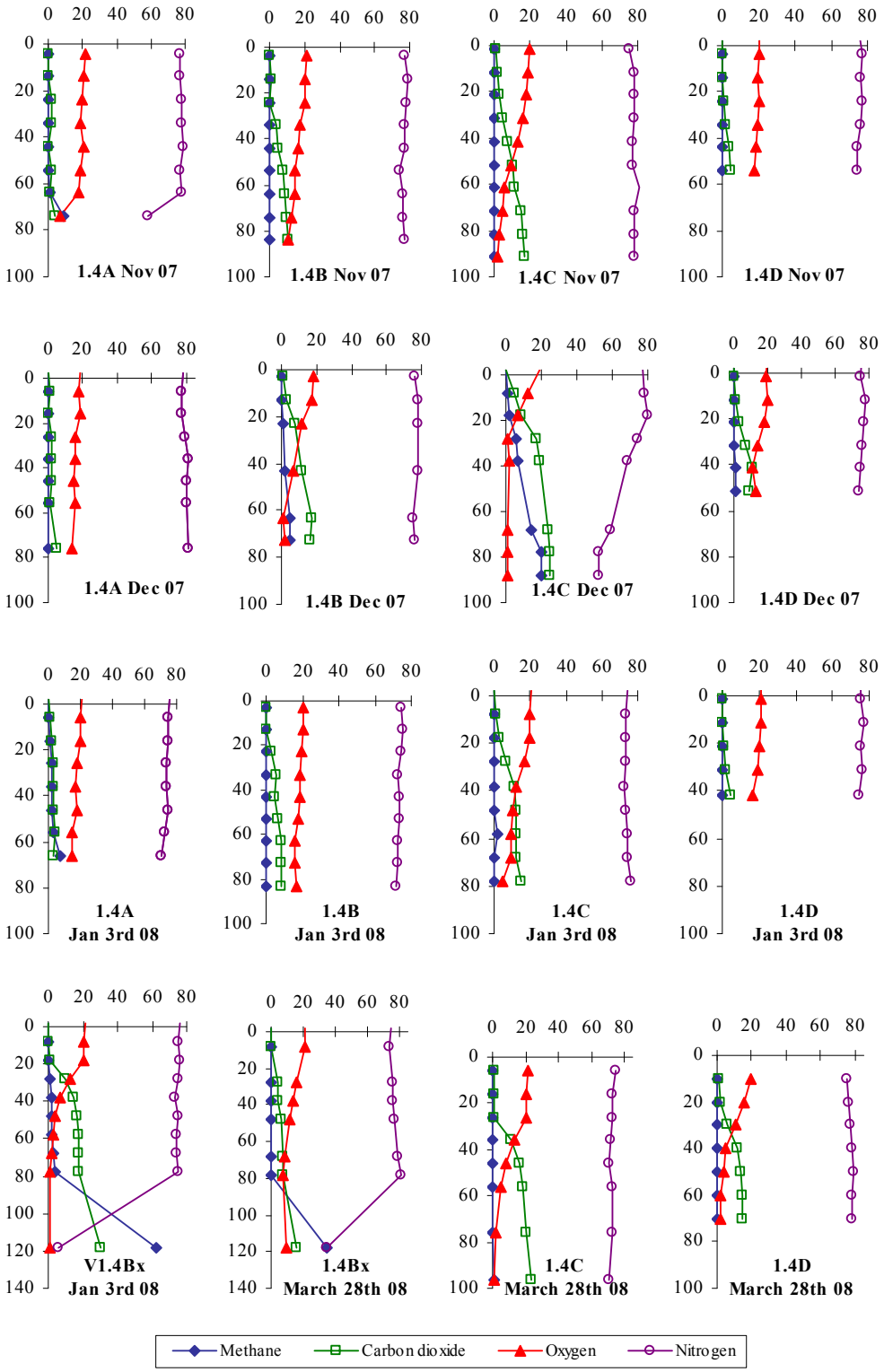
Figure 2: Temperature dependency for compost/peat respiration.

Appendix 4: Additional gas concentration profiles

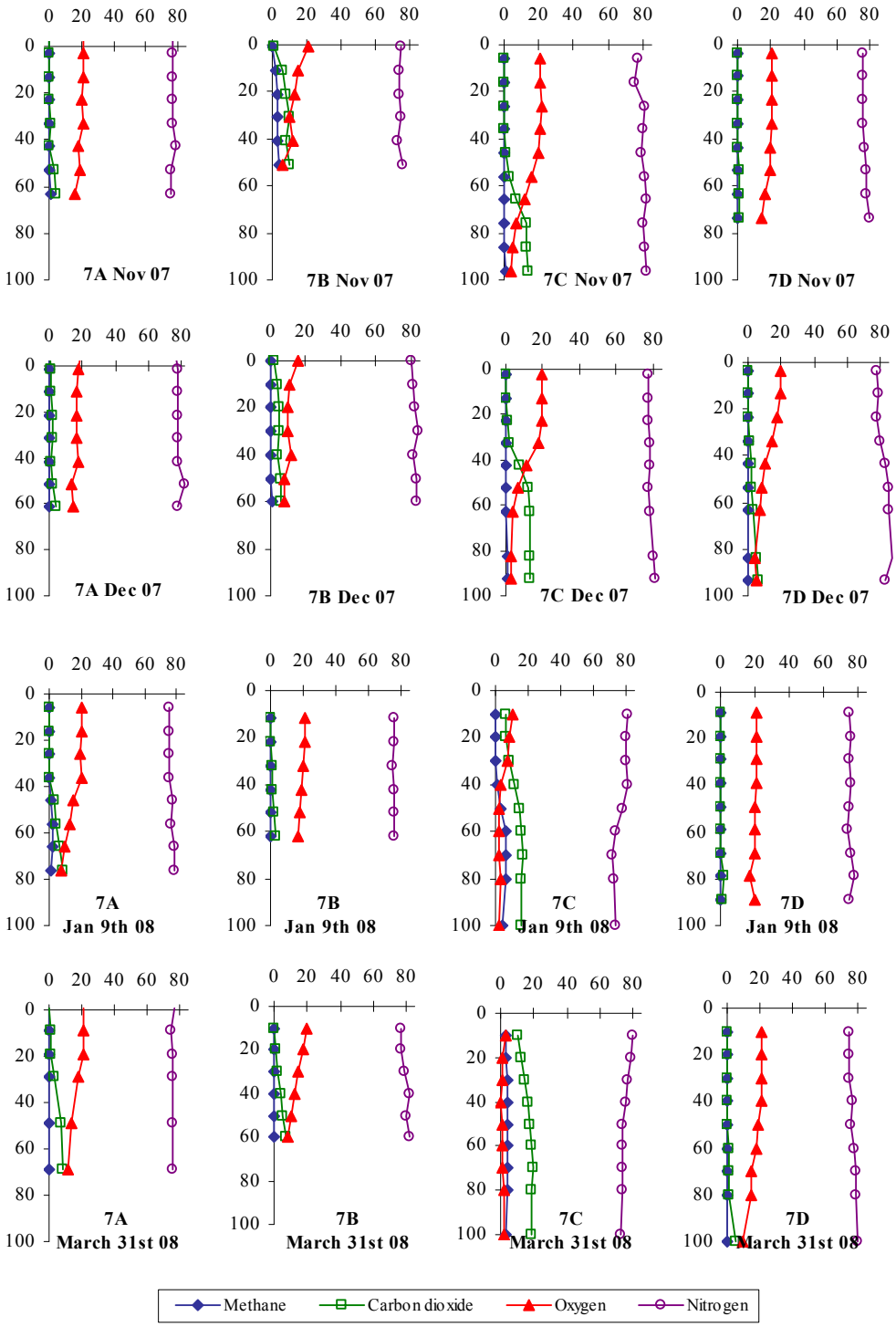
Gas profiles window 1.1



Gas profiles Window 1.4

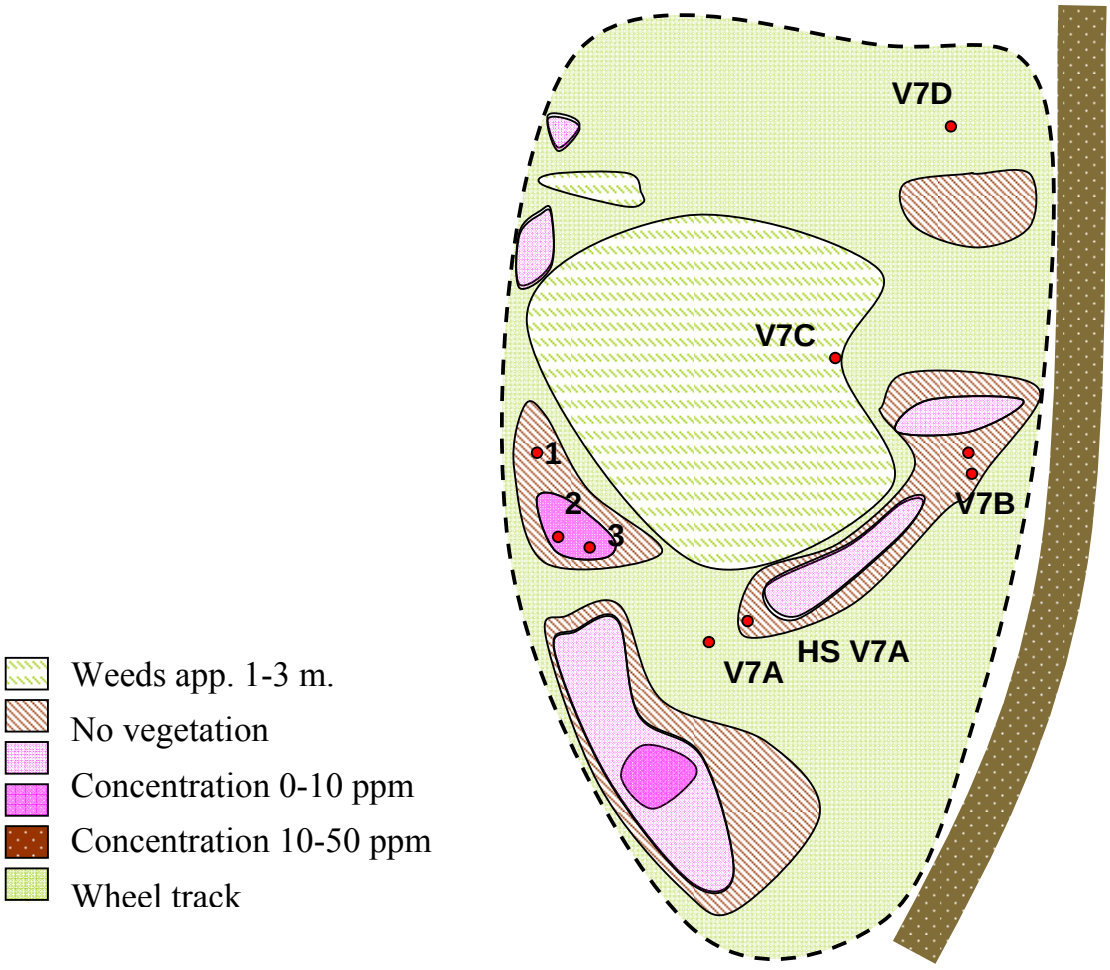


Gas profiles Window 7



Appendix 5: FID screening of window 7

July 10th 2008



Appendix 6: Investigation of leachate wells

-Fakse landfill Friday 31st of October 2008

Goal: Delimitate and quantify the emission of methane and carbon dioxide around the leachate wells.

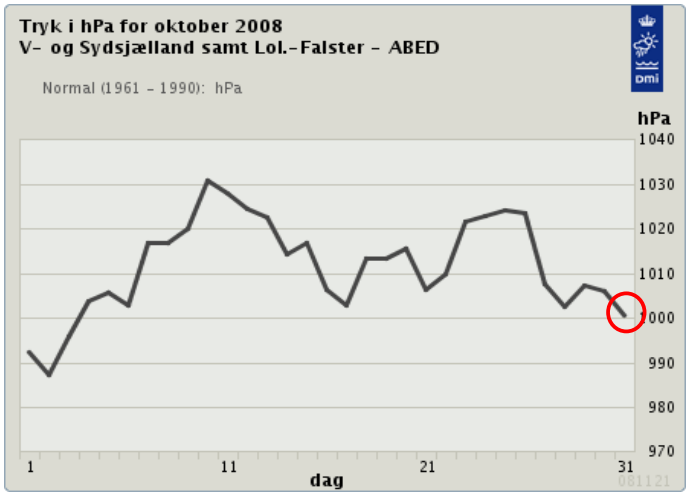
Manpower: Gitte Bukh Pedersen and Bent Skov

Equipment: DUOTEC FID (CH_4) and VAISALA (CO_2)

Method: An initial screening was done, with the FID. Hereafter a few points were selected and flux was measured, by noting linked concentrations and times. It was found that a significant amount of emission still took place around the edges of the wells, but this was not possible to measure with the flux chamber.

Directions have been done assuming that the road dividing the old and the new part is direct north to south. No GPS measuring has been done.

Barometric pressure



D14 (the well at the house)

Around the leachate well: 7-8ppm, 0.2 and 100pmm

10cm from the edge..direction NV: kl10:30 600ppm with the FID. Flux measurement done

184 g CH_4 m^{-2} d^{-1}

31 g CO_2 m^{-2} d^{-1}

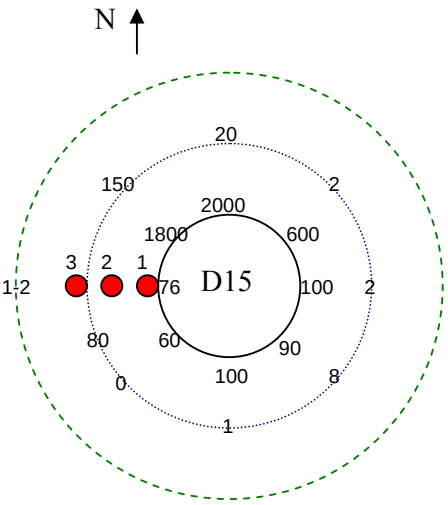
Molar CH_4/CO_2 ratio: 16

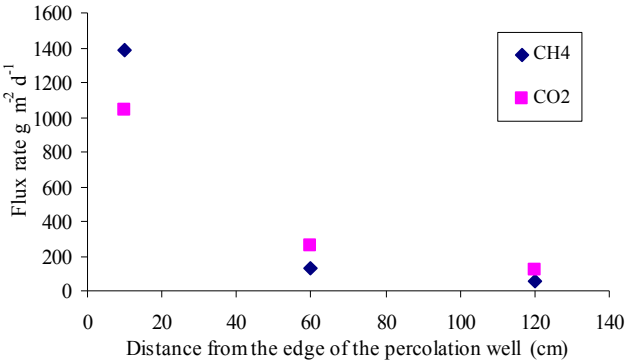
Estimated area: 0.5m^2

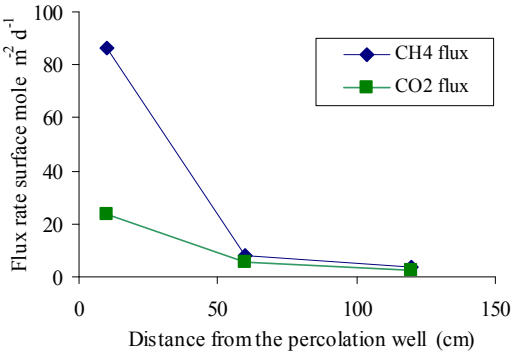
Total emission 92 g CH_4 d^{-1}

D15

R=0.87m


N
20
150
2
2000
1800
600
3
2
1
1 2
76
D15
100
2
80
60
90
0
100
8
1


1600
1400
1200
1000
800
600
400
200
0
Flux rate g m-2 d-1
CH4
CO2
0
20
40
60
80
100
120
140
Distance from the edge of the percolation well (cm)

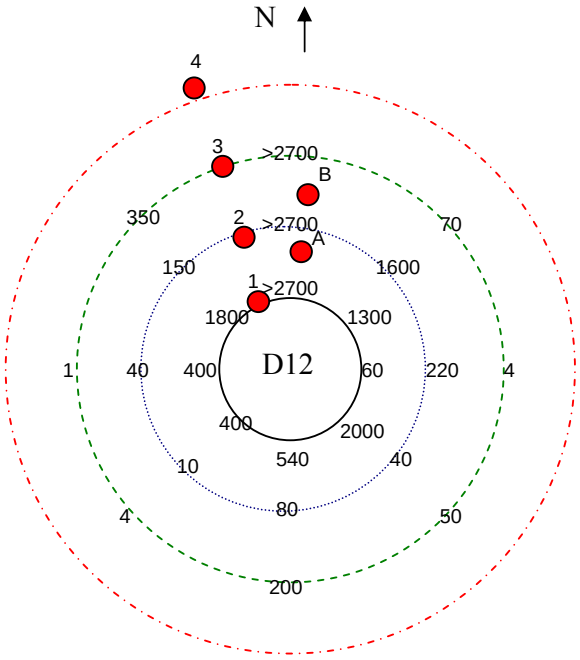

100
80
60
40
20
0
Flux rate surface mole m-2 d-1
CH4 flux
CO2 flux
0
50
100
150
Distance from the percolation well (cm)

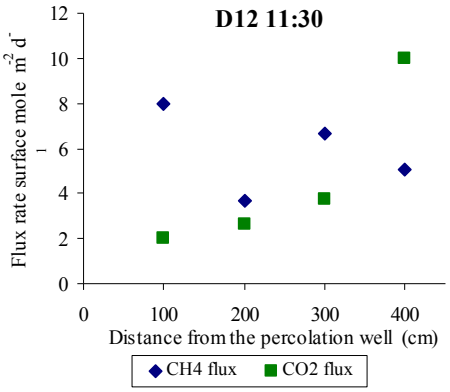
Well D12

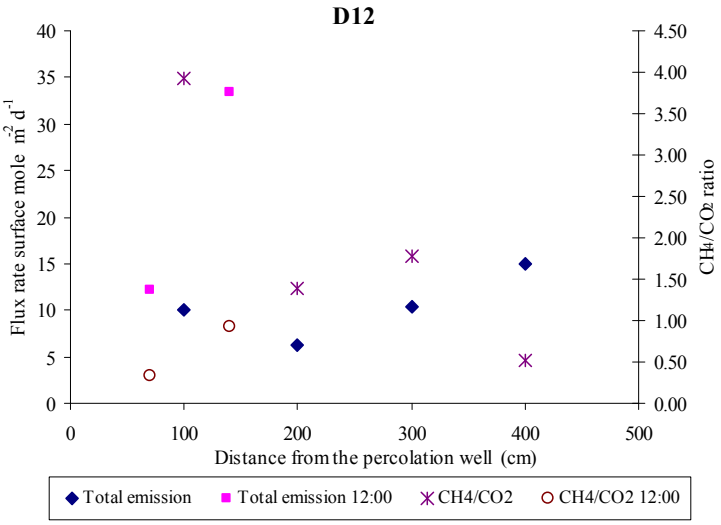
This is the well in the vegetable garden in the corner. Very high emissions are seen, especially along A and B where a bed is placed with wood poles.

Samples for isotopes were taken in flux chamber 3.

R=0.87m





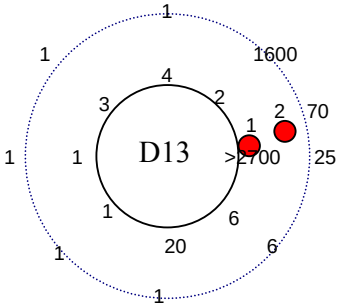


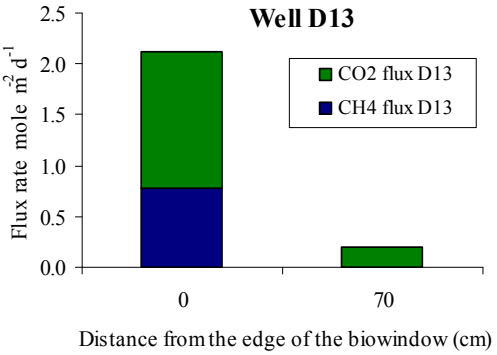
Well D13

It was found that the hotspot is present directly next to the well. Therefore it was not possible to measure the flux. This well is located on the newly covered part of the landfill so the previously placed bentonite is no longer in place.

The second flux chamber (70cm) was very difficult to place as the well was surrounded with wood sticks and branches. Emissions could must likely be reduced my placing clay around the well.

R=0.87m

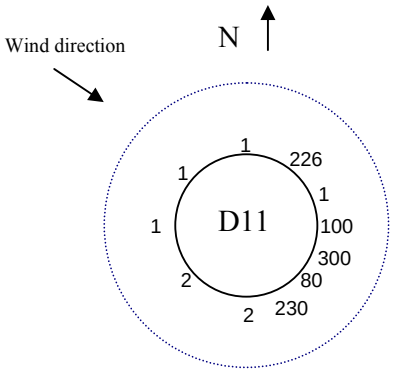




Well D11

It seems that concentrations are in the wind so FID measurements can be due to leakage from the well. Also here the well was surrounded by woods and branched which made it impossible to make a proper flux measurement.

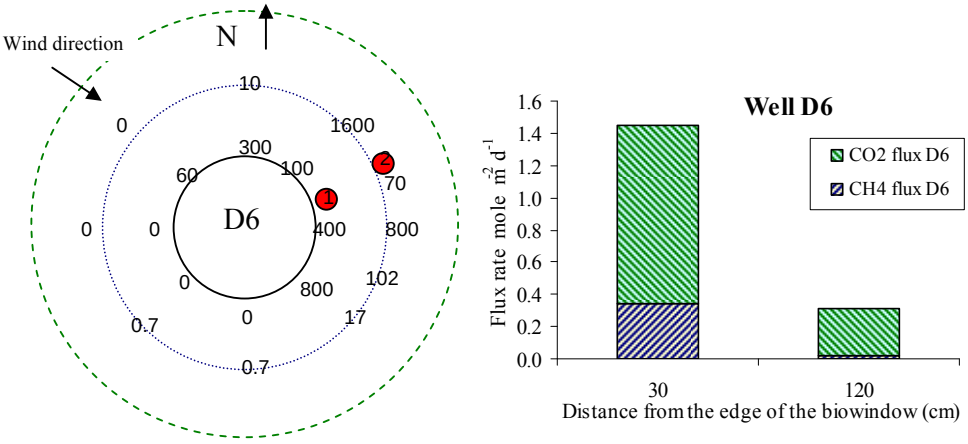
R=0.9m



Well D6

Emissions are clearly seen down wind from the leachate well. The sealing was broken but has been attempted fixed. A hole was still present so most likely this is the origin of the emissions.

R=0.9m



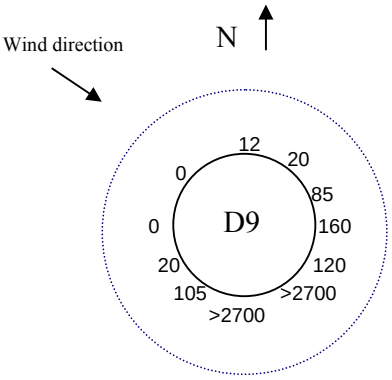
Well D9

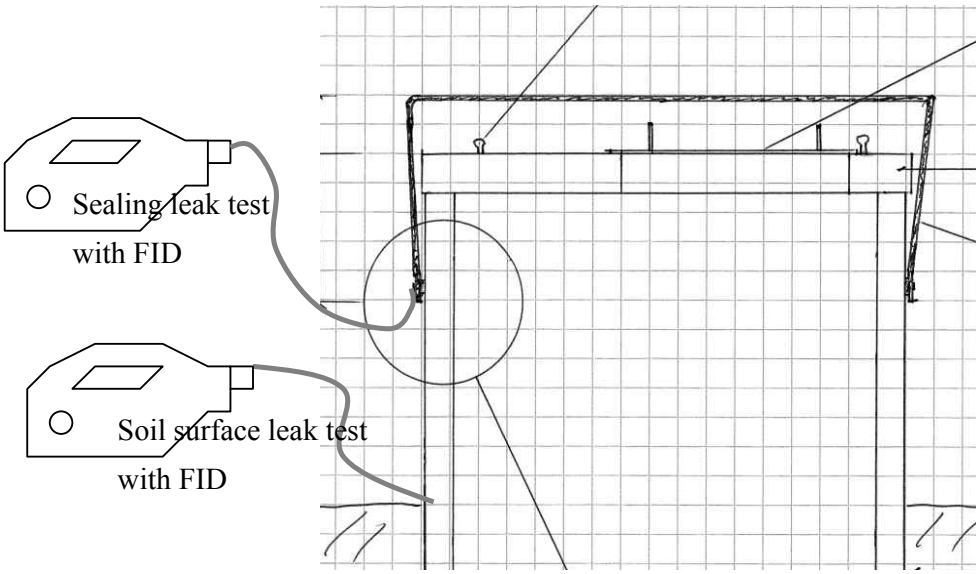
It was tested whether it was leaks in the sealing or cracks along the surrounding soil.

At the sealing conc. >2700 and under the sealing of the well it was 140ppm. (see figure)

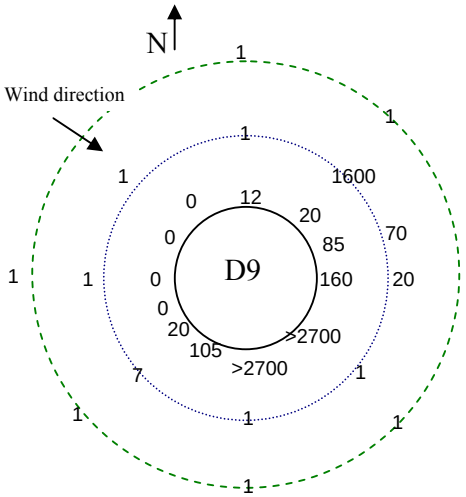
This well was placed in the newly covered part so there was no bentonite around it.

R=0.9m





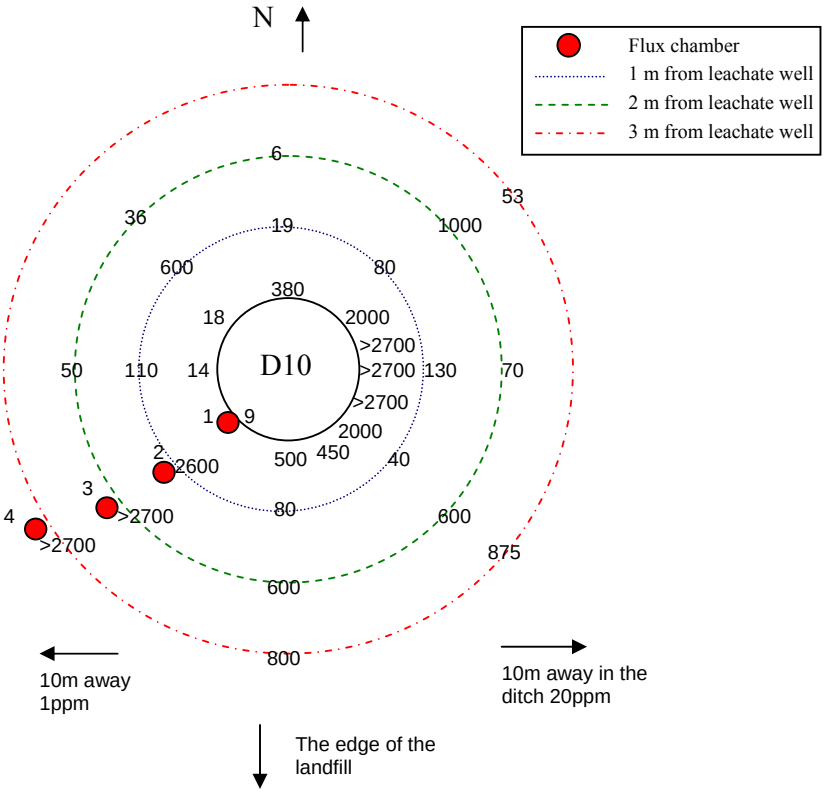
To avoid methane blowing in from a far the hat was used to do the initial screening with the FID. It was placed app. 10sek before reading the conc. The readings for the edge of the well are still done without the hat to be able to get close to the edge.

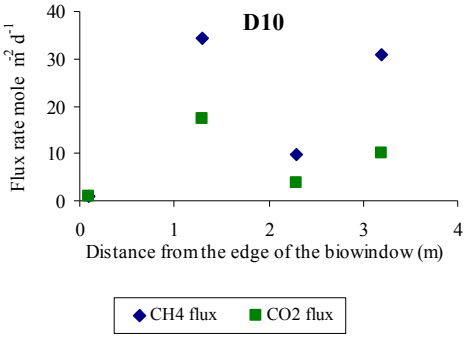


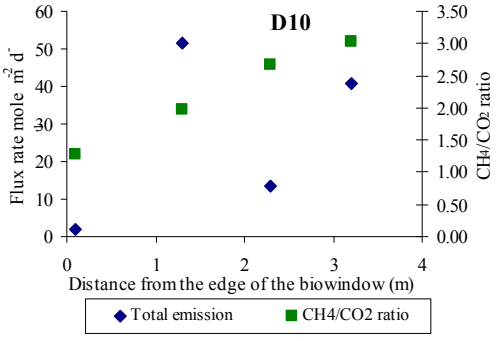
Well D10

Well with very high emissions, especially towards the rim of the landfill. Samples for isotopes are taken in flux chamber measurement no 3.

R=0.9m

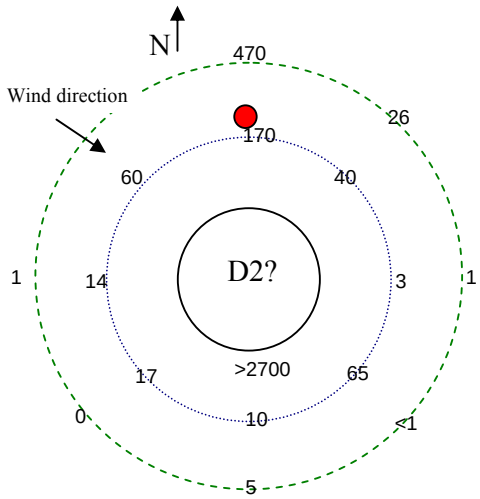




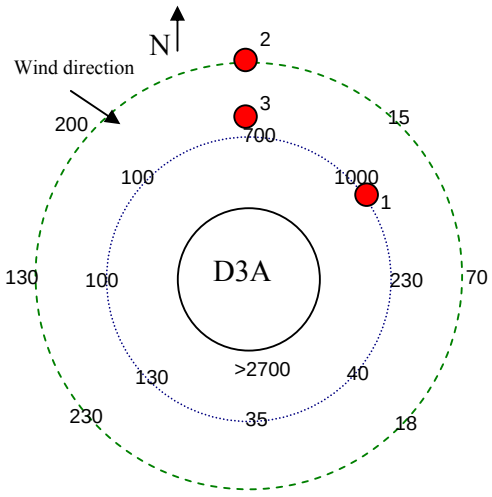


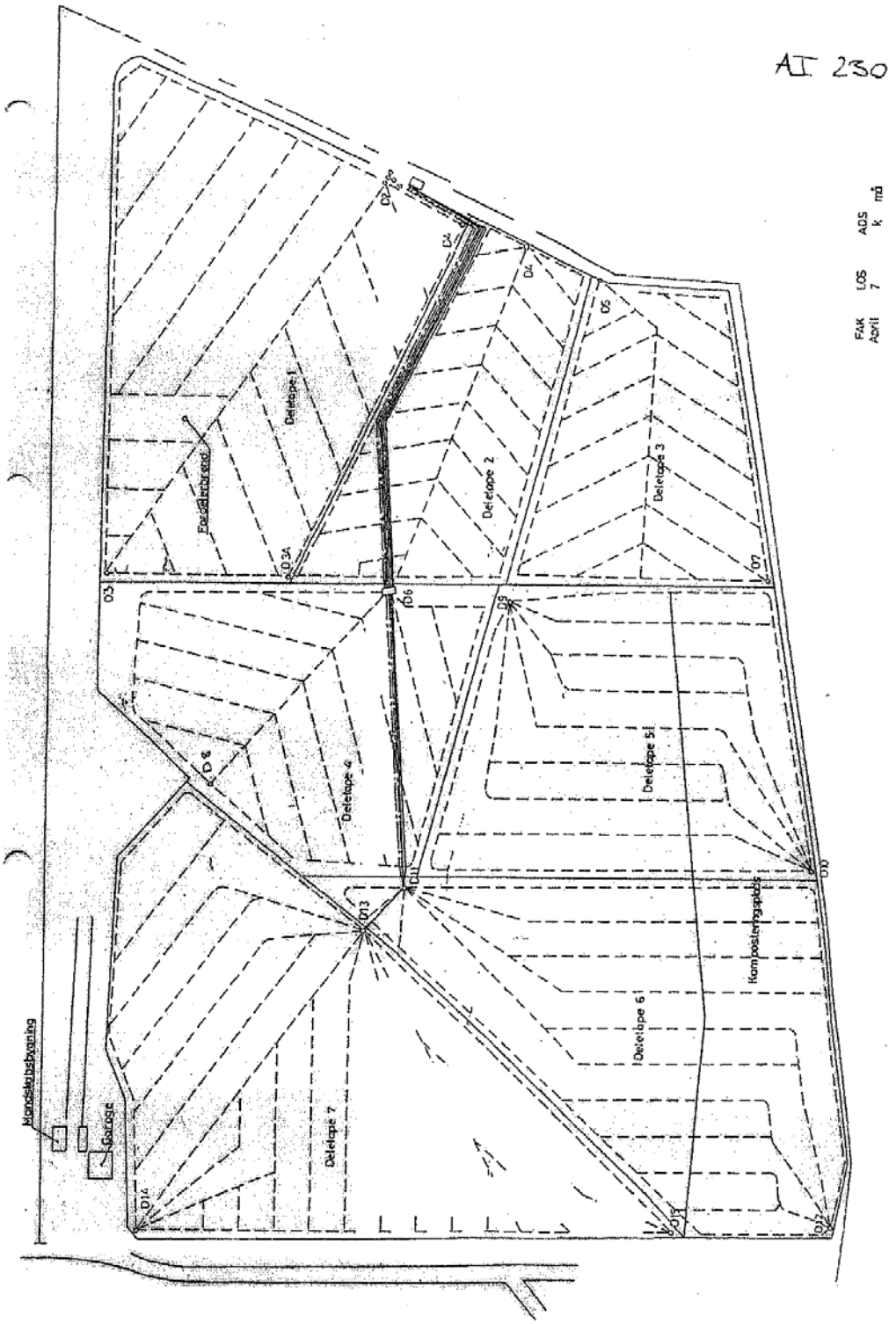
Well D2

R=0.45



	mole CH_4 m^{-2} d^{-1}	mole CO_2 m^{-2} d^{-1}	CH_4/CO_2	mole C m^{-2} d^{-1}
Pumpst-D2	10.79	5.35	2.02	16.15
D3A-1	82.98	136.60	0.61	219.59
D3A-2	0.09	0.88	0.10	0.97
D3A-3	16.02	18.02	0.89	34.04




AI 230
Deletape 1
Deletape 2
Deletape 3
Deletape 4
Deletape 5
Deletape 6
Deletape 7
Kompostering spids
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